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Evaluation of Benchmarks for Conservation Units in Canada's Wild Salmon Policy: Technical Documentation

Évaluation des points de repère servant à évaluer les unités de conservation définis dans la Politique concernant le saumon sauvage du Canada

Carrie A. Holt

Fisheries and Oceans Canada
Pacific Biological Station
3190 Hammond Bay Road
Nanaimo, BC V9T 6N7

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TABLE OF CONTENTS

1. Introduction 1
   1.1 Uncertainties 2
   1.2 Candidate lower benchmarks 3
   1.3 Performance criteria 4
2. Methods 6
   2.1 Simulation models to evaluate lower benchmarks 6
      2.1.1 Population dynamics sub-model 9
      2.1.2 Observation sub-model 13
      2.1.3 Management sub-model 14
      2.1.4 Performance module 15
      2.1.5 Differences between Models 1 and 2 15
   2.2 Model parameterization 15
3. Results 16
   3.1 Model 1: Probability of extirpation over the long term 16
      3.1.1 Lower benchmarks on spawner abundances 16
      3.1.2 Lower benchmarks on fishing mortality 25
   3.2 Model 2: Probability of recovery to S_{MSY} in one (or three) generations 32
      3.2.1 Lower benchmarks on spawner abundances 32
      3.2.2 Lower benchmarks on fishing mortality 40
4. Recommendations 48
5. Literature cited 49

TABLE OF FIGURES

Figure 1. Simulation modelling framework used to evaluate the probability of extirpation over the long term (a) and probability of recovery to S_{MSY} (b, next page) for lower benchmarks on spawner abundances. S_y is the spawner abundance in brood year y, R is recruitment, t is year of recruitment, R_0 is observed recruitment, h is target harvest rate derived from target spawner abundances, S_{target}, and observed recruitment, and h' is the realized harvest rate (i.e., harvest with outcome uncertainty). Note, panel (b) does not include an "Observation sub-model" because for that model evaluated probability of recovery under a scenario of no directed fishing, and so observations of abundance were not required. 8

Figure 2. Probabilities of extirpation over the long term (100 years) for simulated populations of Pacific salmon under a constant escapement policy equal to the lower benchmarks derived from spawner abundances at various percentages of R_{MSY} (black lines) over a gradient in equilibrium stock sizes (X-axis). Three other lower benchmarks are shown: spawner abundances, S, at 50% of R_{MAX} (red line), 40% of S_{MSY} (blue line), and spawner abundance resulting in recovery to S_{MSY} in one generation without fishing under equilibrium conditions, S_{gen} (green line). 17

Figure 3. Probabilities of extirpation, p, over the long term (100 years) for unproductive (mean Ricker "a" parameter = 0.5, or 1.7 recruits/spawner at low spawner abundances) (a), moderately productive (mean Ricker "a" parameter = 1.5, or 4.5 recruits/spawner at low spawner abundances) (b), and highly productive (mean Ricker "a" parameter = 2.0, or 7.4 recruits/spawner at low spawner abundances) (c) simulated populations of Pacific salmon under a constant escapement policy equal to the lower benchmarks derived from spawner abundances at various percentages of R_{MSY} (black lines, ranging from 10% (top line) to 90% (bottom line)) over a gradient in equilibrium stock sizes (X-axis). Three other lower benchmarks are shown, as described in the caption to Fig.2: S at 50% of R_{MAX} (red line), 40% of S_{MSY} (blue line), and S_{gen} (green line). 18

Figure 4. Probabilities of extirpation over the long term (10 0 years) for simulated populations of Pacific salmon under a constant escapement policy equal to the lower benchmark derived from S_{gen} (spawner abundances that will result in recovery to S_{MSY} in one generation under equilibrium conditions) and four assumptions about the trends in stock productivity (Ricker "a" parameter): no trend (thick solid line); linear increase over time (thin solid line); linear decline over time (dashed line); and cyclic pattern (dotted line), over a gradient in equilibrium stock sizes (X-axis). 19

Figure 5. Probabilities of extirpation over the long term (100 years) for simulated populations of Pacific salmon under a constant escapement policy equal to the lower benchmark derived from S_{gen} (spawner abundances that will result in recovery to S_{MSY} in one generation under equilibrium conditions) and four assumptions about the stock-recruitment model: Ricker model (thin solid line), Ricker model with autocorrelation and depensatory mortality at low spawner abundances (thick solid line), Beverton-Holt model (dashed line), and Larkin model (dotted line), over a gradient in equilibrium stock sizes (X-axis). 20

Figure 6. Probabilities of extirpation over the long term (100 years) for simulated populations of Pacific salmon under a constant escapement policy equal to the lower

benchmark derived from S_{gen} (spawner abundances that will result in recovery to S_{MSY} in one generation under equilibrium conditions) and three assumptions about the spawner abundance below which depensatory mortality occurs: 500 fish (thick solid line); 1000 fish (thin solid line); 7000 (dashed line), over a gradient in equilibrium stock sizes (X-axis). 21
Figure 7. Probabilities of extirpation over the long term (100 years) for simulated populations of Pacific salmon under a constant escapement policy equal to the lower benchmark derived from S_{gen} (spawner abundances that will result in recovery to S_{MSY} in one generation under equilibrium conditions) and two assumptions about the magnitude of observation errors: standard deviation between actual and observed abundance = 0.19 (thin solid line) and 0.38 (thick solid line), over a gradient in equilibrium stock sizes (X-axis). 22
Figure 8. Probabilities of extirpation over the long term (100 years) for simulated populations of Pacific salmon under a constant escapement policy equal to the lower benchmark derived from S_{gen} (spawner abundances that will result in recovery to S_{MSY} in one generation under equilibrium conditions) and three assumptions about the number of years of historical data used to estimate R_{MSY} when deriving the lower benchmark (corresponding to the magnitude of assessment uncertainty): 30 years (low assessment uncertainty, thin solid line), 20 years (moderate assessment uncertainty, thick solid line), and 15 years (high assessment uncertainty, dashed line), over a gradient in equilibrium stock sizes (X-axis). 23
Figure 9. Probabilities of extirpation over the long term (100 years) for simulated populations of Pacific salmon under a constant escapement policy equal to the lower benchmark derived from S_{gen} (spawner abundances that will result in recovery to S_{MSY} in one generation under equilibrium conditions) and two assumptions about the magnitude of outcome uncertainty: standard deviation between realized harvest rates and targets = 0.097 (thin solid line) and 0.19 (thick solid line), over a gradient in equilibrium stock sizes (X-axis). 24
Figure 10. Probabilities of extirpation over the long term (100 years) for simulated populations of Pacific salmon under a constant escapement policy equal to the lower benchmark derived from S_{gen} (spawner abundances that will result in recovery to S_{MSY} in one generation under equilibrium conditions) and three assumptions about the lower limit on harvest rate, h_t, (due to non-target fishing mortality, e.g., test-fishery and by-catch): low $h_t = 0.02$ (thin solid line), moderate $h_t = 0.1$ (thick solid line), and high $h_t = 0.2$ (dashed line), over a gradient in equilibrium stock sizes (X-axis). 25
Figure 11. Probabilities of extirpation over the long term (100 years) for simulated populations of Pacific salmon under a constant fishing mortality rate policy equal to the lower benchmarks derived from various percentages of F_{MSY} (black lines) over a gradient in equilibrium stock sizes (X-axis). Three other lower benchmarks are shown: F_{MSY} (red line, equivalent to 100% F_{MSY}), the maximum $\log_e$(recruits/spawner) at low spawner abundances (i.e., Ricker "a" parameter) (F_{MAX}, blue line), and the median $\log e$(recruits/spawner) (F_{MED}, green line). 26
Figure 12. Probabilities of extirpation, p, over the long term (100 years) for unproductive (mean Ricker "a" parameter = 0.5, or 1.7 recruits/spawner at low spawner abundances) (a), moderately productive (mean Ricker "a" parameter = 1.5, or 4.5

recruits/spawner at low spawner abundances) (b), and highly productive (mean Ricker "a" parameter = 2.0, or 7.4 recruits/spawner at low spawner abundances) (c) simulated populations of Pacific salmon under a constant escapement policy equal to the lower benchmarks derived from various percentages of F_{MSY} (black lines, ranging from 150% (top line) to 50% (bottom line)) over a gradient in equilibrium stock sizes (X-axis). Three other lower benchmarks are shown, as described in the caption to Fig.11: F_{MSY} (red line), F_{MAX} (blue line), and F_{MED} (green line). 27
Figure 13. Probabilities of extirpation over the long term (100 years) for simulated populations of Pacific salmon under a constant fishing mortality rate policy equal to the lower benchmarks, F_{MSY}, and four assumptions about the trends in stock productivity (Ricker "a" parameter): no trend (thick solid line); linear increase over time (thin solid line); linear decline over time (dashed line); and cyclic pattern (dotted line), over a gradient in equilibrium stock sizes (X-axis)..... 28
Figure 14. Probabilities of extirpation over the long term (100 years) for simulated populations of Pacific salmon under a constant fishing mortality rate policy equal to the lower benchmarks, F_{MSY}, and four assumptions about the stock-recruitment model: Ricker model (thin solid line), Ricker model with autocorrelation and depensatory mortality at low spawner abundances (thick solid line), Beverton-Holt model (dashed line), and Larkin model (dotted line), over a gradient in equilibrium stock sizes (X-axis). Lines for the Ricker, Beverton-Holt, and Larkin models lie almost on top of each other near the bottom X-axis. 29
Figure 15. Probabilities of extirpation over the long term (100 years) for simulated populations of Pacific salmon under a constant fishing mortality rate policy equal to the lower benchmarks, F_{MSY}, and three assumptions about the spawner abundance below which depensatory mortality occurs: 500 fish (thick solid line); 1000 fish (thin solid line); 7000 (dashed line), over a gradient in equilibrium stock sizes (X-axis)..... 30
Figure 16. Probabilities of extirpation over the long term (100 years) for simulated populations of Pacific salmon under a constant fishing mortality rate policy equal to the lower benchmarks, F_{MSY}, and three assumptions about the number of years of historical data used to estimate F_{MSY} when deriving the lower benchmark (corresponding to the magnitude of assessment uncertainty): 30 years (thin solid line), 20 years (thick solid line), and 15 years (dashed line), over a gradient in equilibrium stock sizes (X-axis). 31
Figure 17. Probabilities of extirpation over the long term (100 years) for simulated populations of Pacific salmon under a constant fishing mortality rate policy equal to the lower benchmarks, F_{MSY}, and two assumptions about the magnitude of outcome uncertainty: standard deviation between realized harvest rates and targets = 0.097 (thin solid line) and 0.19 (thick solid line), over a gradient in equilibrium stock sizes (X-axis). 32
Figure 18. Probabilities of recovery over one (a) and three (b) generation(s) for simulated populations of Pacific salmon from lower benchmark on spawner abundances listed on the X-axis, in the absence of commercial and recreational fishing. Lower benchmarks derived from spawner abundances at various percentages of R_{MSY} (black solid circles) are compared with three other lower benchmarks: spawner abundances at 50% of R_{MAX} (red circle), 40% of S_{MSY} (blue circle), and spawner

abundance resulting in recovery to S_{MSY} in one generation without fishing under equilibrium conditions, S_{gen} (green circle). 33
Figure 19. Probabilities of recovery over one generation for unproductive (hollow grey and coloured circles), moderately productive (solid grey and coloured circles), and highly productive (solid black and coloured circles with black outline) simulated populations of Pacific salmon from lower benchmarks on spawner abundances listed on the X-axis in the absence of commercial and recreational fishing. Lower benchmarks are the same as described in the caption to Fig. 18. 34
Figure 20. Probabilities of recovery over one generation for simulated populations of Pacific salmon that have constant productivity (Ricker "*a*" parameter) over time (hollow grey and coloured circles), linearly increasing productivity (solid grey and coloured circles), linearly declining productivity (solid black and coloured circles with black outline), and cyclic patterns in productivity (black and coloured asterisks), from lower benchmarks on spawner abundances listed on the X-axis in the absence of commercial and recreational fishing. Note, points are almost coincident because magnitudes of the changes in productivity are small over one generation. Lower benchmarks are the same as described in the caption to Fig. 18. 35
Figure 21. Probabilities of recovery over one generation for simulated populations of Pacific salmon that recruit according to a Ricker model (solid grey and coloured circles), a Ricker model with autocorrelation and depensation (solid black and coloured circles with black outline), a Beverton-Holt model (hollow grey and coloured circles), and a Larkin model (black and coloured asterisks), from lower benchmarks on spawner abundances listed on the X-axis in the absence of commercial and recreational fishing. Lower benchmarks are the same as described in the caption to Fig. 18. 36
Figure 22. Probabilities of recovery over one generation for simulated populations of Pacific salmon that recruit according to a Ricker model with autocorrelation and depensatory mortality at low spawner abundances, i.e., below 500 spawners, 1000 spawners, and 7000 spawners, from lower benchmarks on spawner abundances listed on the X-axis, in the absence of commercial and recreational fishing. Note, points for different threshold levels below which depensation occurs are exactly coincident (i.e., the probability of recovery is insensitive to threshold level). Lower benchmarks are the same as described in the caption to Fig. 18. 37
Figure 23. Probabilities of recovery over one generation for simulated populations of Pacific salmon from lower benchmarks on spawner abundances listed on the X-axis, derived from historical time series of length 15 years (hollow grey and coloured circles), 20 years (solid grey and coloured circles), and 30 years (solid black and coloured circles with black outline), in the absence of commercial and recreational fishing. Lower benchmarks are the same as described in the caption to Fig. 18..... 38
Figure 24. Probabilities of recovery over one generation for simulated populations of Pacific salmon with low outcome uncertainties (solid grey and coloured circles) and high outcome uncertainties (solid black and coloured circles with black outline), from lower benchmarks on spawner abundances listed on the X-axis, in the absence of commercial and recreational fishing. Lower benchmarks are the same as described in the caption to Fig. 18. 39

Figure 25. Probabilities of recovery over one generation for simulated populations of Pacific salmon from lower benchmarks on spawner abundances listed on the X-axis, in the absence of commercial and recreational fishing but with non-targeted harvest rate (e.g., from a test fishery and by-catch) of $h_t = 0.02$ (hollow grey and coloured circles), $h_t = 0.1$ (solid grey and coloured circles) and $h_t = 0.2$ ((solid black and coloured circles with black outline). Lower benchmarks are the same as described in the caption to Fig. 18. 40
Figure 26. Probabilities of recovery over one (a) and three (b) generation(s) for simulated populations of Pacific salmon managed according to the lower benchmark on fishing mortality listed on the X-axis, in the absence of commercial and recreational fishing. Lower benchmarks derived from fishing mortality at various percentages of F_{MSY} (black solid circles) are compared with three other lower benchmarks: F_{MSY} (red circle), maximum $\log_e(R/S)$ at low spawner abundances, F_{MAX} (blue circle), and median $\log_e(R/S)$, F_{MED} (green circle). 41
Figure 27. Probabilities of recovery over one generation for unproductive (hollow grey and coloured circles), moderately productive (solid grey and coloured circles), and highly productive (solid black and coloured circles with black outline) simulated populations of Pacific salmon managed according to the lower benchmarks on fishing mortality listed on the X-axis, in the absence of commercial and recreational fishing. Lower benchmarks are the same as described in the caption to Fig. 26..... 42
Figure 28. Probabilities of recovery over one generation for simulated populations of Pacific salmon that have constant productivity (Ricker "a" parameter) over time (hollow grey and coloured circles), linearly increasing productivity (solid grey and coloured circles), linearly declining productivity (solid black and coloured circles with black outline), and cyclic patterns in productivity (black and coloured asterisks), managed according to the lower benchmarks on fishing mortality listed on the X-axis in the absence of commercial and recreational fishing. Note, points are almost coincident because magnitude of the changes in productivity are small over one generation. Lower benchmarks are the same as described in the caption to Fig. 26..... 43
Figure 29. Probabilities of recovery over one generation for simulated populations of Pacific salmon that recruit according to a Ricker model (solid grey and coloured circles), a Ricker model with autocorrelation and depensation (solid black and coloured circles with black outline), a Beverton-Holt model (hollow grey and coloured circles), and a Larkin model (black and coloured asterisks), managed according to the lower benchmarks on fishing mortality listed on the X-axis in the absence of commercial and recreational fishing. Lower benchmarks are the same as described in the caption to Fig. 26. 44
Figure 30. Probabilities of recovery over one generation for simulated populations of Pacific salmon that recruit according to a Ricker model with autocorrelation and depensatory mortality at low spawner abundances, i.e., below 500 spawners, 1000 spawners, and 7000 spawners, managed according to the lower benchmarks on fishing mortality listed on the X-axis, in the absence of commercial and recreational fishing. Note, points for different threshold levels below which depensation occurs are exactly coincident (i.e., the probability of recovery is insensitive to threshold level). Lower benchmarks are the same as described in the caption to Fig. 26..... 45

Figure 31. Probabilities of recovery over one generation for simulated populations of Pacific salmon managed according to the lower benchmarks on fishing mortality listed on the X-axis, derived from historical time series of length 15 years (hollow grey and coloured circles), 20 years (solid grey and coloured circles), and 30 years (solid black and coloured circles with black outline), in the absence of commercial and recreational fishing. Lower benchmarks are the same as described in the caption to Fig. 26. 46
Figure 32. Probabilities of recovery over one generation for simulated populations of Pacific salmon with low outcome uncertainties (solid grey and coloured circles) and high outcome uncertainties (solid black and coloured circles with black outline), managed according to the lower benchmarks on fishing mortality listed on the X-axis, in the absence of commercial and recreational fishing. Lower benchmarks are the same as described in the caption to Fig. 26..... 47

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ABSTRACT

Canada's Wild Salmon Policy requires that quantifiable metrics of biological status and benchmarks along those metrics that delineate Red, Amber, and Green zones of status be established for all Conservation Units. Although candidate benchmarks have been identified from the scientific literature and previous management experience, they have not been evaluated in terms of their ability to meet the goals of the Wild Salmon Policy. Using a simulation model, we evaluated lower benchmarks on two classes of indicators (abundances and fishing mortality relative to productivity) on two performance metrics: the probability of extirpation over the long term and the probability of recovery to a target. This technical document provides the methodology and results for those analyses and is a companion document to the overall synthesis paper "Indicators of Status and Benchmarks for Conservation Units in Canada's Wild Salmon Policy" (Holt et al. 2009). We considered the "worst-case" management scenario, with management decisions corresponding to CUs being depleted to the lower benchmark each year. Although unrealistic, this assumption provides an upper limit on the probability of extirpation and lower limit on the probability of recovery. We found that for metrics of spawner abundances, the lower benchmark, spawner abundance that will result in recovery to S_{MSY} (spawner abundance at maximum sustained yield) in one generation under equilibrium conditions (S_{gen}), was associated with a relatively low probability of extirpation (probability <25%) over 100 years (for populations with equilibrium abundances > 15 000 spawners) and high probability of recovery to S_{MSY} within three generations (probability >75%) when uncertainties in all major components of the fishery system were accounted for. Furthermore, the probability of extirpation for S_{gen} was more robust to variability in stock productivity compared with benchmarks calculated from proportions of S_{MSY}. For metrics of fishing mortality, the lower benchmark F_{MSY} (fishing mortality at maximum sustained yield) was associated with a relatively low probability of extirpation (probability <25%) over 100 years for populations with equilibrium abundances > 30 000 spawners, and high probability of recovery to S_{MSY} within three generations (probability >75%), and its performance was more robust to variability in stock productivity than other benchmarks on fishing mortality derived from the scientific literature. Based on those results and a risk classification scheme developed in DFO's Fishery Decision-Making Framework Incorporating the Precautionary Approach (2009), we suggest deriving lower benchmarks on spawner abundances from S_{gen} and lower benchmarks on fishing mortality from F_{MSY}. Further work will be required to identify specific risk tolerances of stakeholders in order to better inform the choice of lower benchmarks.

RÉSUMÉ

La Politique concernant le saumon sauvage du Canada exige que des paramètres quantifiables pour évaluer l'état biologique ainsi que des points de repère pour délimiter les trois zones d'état (rouge, ambre et vert) soient établis pour toutes les unités de conservation. Bien que des points de repère probables aient été déterminés à partir de l'examen de la documentation scientifique et d'une expérience de gestion précédente, ils n'ont pas fait l'objet d'une évaluation sur le plan de leur capacité à atteindre les objectifs visés par la Politique concernant le saumon sauvage. Au moyen d'un modèle de simulation, on a évalué les points de repère inférieurs de deux catégories d'indicateurs (l'abondance et la mortalité par pêche relativement à la productivité) pour deux paramètres liés à la performance : la probabilité de disparition d'un endroit donné à long terme et la probabilité de rétablissement correspondant à un objectif. Ce document technique présente la méthode et les résultats de ces analyses et est un document d'accompagnement à l'ouvrage de synthèse générale intitulé « Indicators of Status and Benchmarks for Conservation Units in Canada's Wild Salmon Policy » (Holt et coll., 2009). On a envisagé le pire scénario de gestion avec des décisions de gestion correspondant aux unités de conservation étant appauvries au point de repère inférieur chaque année. Bien qu'elle soit peu réaliste, cette hypothèse procure un seuil supérieur relatif à la probabilité de disparition et un seuil inférieur relatif à la probabilité de rétablissement. En ce qui concerne les paramètres de l'abondance de reproducteurs, on a découvert que le point de repère le plus bas, l'abondance de reproducteurs qui se traduira par le rétablissement à SMSY (abondance de reproducteurs au rendement maximal soutenable) en une génération dans des conditions d'équilibre (Sgen), était associé à une probabilité relativement faible de disparition (probabilité < 25 %) sur 100 ans (pour les populations affichant un niveau d'abondance équilibré > 15 000 reproducteurs) et une forte probabilité de rétablissement à SMSY en trois générations (probabilité > 75 %), lorsqu'on tenait compte des incertitudes liées à toutes les composantes principales du système de pêche. De plus, la probabilité de disparition pour Sgen était davantage liée à la variabilité de productivité du stock comparativement aux points de repère calculés à partir des proportions de SMSY. Quant aux paramètres relatifs à la mortalité par pêche, le point de repère inférieur FMSY (mortalité par pêche au rendement maximal soutenable) était associé à une probabilité relativement faible de disparition (probabilité < 25 %) sur plus de 100 ans pour des populations affichant un niveau d'abondance équilibré > 30 000 reproducteurs, et une forte probabilité de rétablissement à SMSY en trois générations (probabilité > 75 %), et sa performance était davantage liée à la variabilité de productivité du stock que les autres points de repère relatifs à la mortalité par pêche issus des documents scientifiques. À partir de ces résultats et d'un schéma de classification fondée sur le risque élaboré en vertu du cadre décisionnel pour les pêches intégrant l'approche de précaution (2009) du MPO, on suggère de calculer les points de repère inférieurs pour l'abondance de reproducteurs à partir de Sgen et les points de repère inférieurs pour la mortalité par pêche à partir de FMSY. Des études supplémentaires seront nécessaires afin de déterminer la tolérance particulière à l'égard des risques des intervenants dans le but de mieux définir le choix des points de repère inférieurs.

1. INTRODUCTION

Numerous lower benchmarks have been proposed to assess status of Conservation Units for the Wild Salmon Policy, but those benchmarks have not been evaluated in a consistent, probabilistic way (i.e., incorporating uncertainties). To evaluate the performance of lower benchmarks, we adapted the nine steps identified in the idealized assessment framework for identifying benchmarks (Table 1). Specifically, using a simulation modelling approach, we compared the performances of benchmarks on two criteria derived from the Wild Salmon Policy, the probability of extirpation over the long term and the probability that the CU will rebuild to levels where harvest can provide, on an average annual basis, the maximum annual catch, given existing environmental conditions (i.e., probability of recovery to S_{MSY}). We did this by developing an operating model, which is a mathematical abstraction of the true fisheries system accounting for all known uncertainties. In the operating model, we assumed the most aggressive harvest strategy possible that still recognized the lower benchmark (i.e., that was associated with the highest possible probability of extirpation and lowest possible probability of recovery). In other words, the harvest strategy was associated with the worst-case performance. For the benchmarks on fishing mortality, that harvest strategy was a constant fishing mortality policy equivalent to the lower benchmark (see Section 1.3 for more details). For benchmarks on spawner abundances, the harvest strategy was a constant escapement policy equivalent to the lower benchmark, with one exception when evaluating the probability of recovery to a target (as described in Section 1.3). All other possible harvest strategies that recognize those lower benchmarks but adapt escapement or fishing mortality according to observed abundances or catches above that benchmark, will result in improved performance (a lower probability of extirpation and higher probability of recovery). Although these harvest strategies may be unrealistic, they demonstrate the long-term properties of the benchmarks under pessimistic assumptions about the ability of fishery management to restrict effort. Therefore, the simulation model results represent a lower limit on possible performance. Evaluating all possible harvest strategies in a simulation model is beyond the scope of this report, but will be a necessary step before implementing those rules in the fishery.

Table 1 Steps for determining a precautionary lower benchmark in an idealized assessment framework for an example reference frame (biological yield) and goal (maintenance of maximum yield). The providers are either Fisheries Management, FM, or Science

Step	Provider	Input	Output
1. Reference frame	FM (WSP)	Policy specification	Specified as biological production (i.e., yield)
2. Goal or endpoint	FM (WSP)	Policy specification	Maintenance of maximum yield adjusted for current environmental conditions
3. Time frame to achieve goal or endpoint	FM	Unspecified	Number of years
4. Fishery management actions	FM	Unspecified	Actions such as 10% total exploitation rate
5. Model relating current state to a future state	Science	Production model	Ricker stock-recruitment model
6. Deterministic upper benchmark	Science	WSP specification	Example, *MSY*
7. Deterministic lower benchmark	Science	Outputs of steps 2, 3, 4, & 6	Lower benchmark
8. Incorporate uncertainty into lower benchmark	Science	Quantification of known uncertainties including model choice, parameter estimation, current state, future state of modifiers (environment), and outcome/implementation uncertainty	Function relating possible values of the lower benchmark to the probability of achieving the goal within the time allowed
9. Choice of risk tolerance	FM	Output of step 8	Selected lower benchmark

1.1 Uncertainties

By incorporating uncertainties in all major components of the fisheries system (population dynamics, observations of abundances, and management) the operating model provides a basis for evaluating lower benchmarks on probabilistic criteria and for assessing risks associated with those benchmarks. Uncertainties were incorporated in two ways. First, the simulation model was iterated over Monte Carlo trials to generate distributions of abundances in each year instead of point values. Second, the "base-case" simulation model was rerun according to different assumptions about parameter values and model structure (including assumptions about relationship between spawner abundances and recruitment, degree of depensatory mortality at low spawner abundances, trends in productivity, magnitude of observation errors, length of historical time series used to estimate benchmarks, and deviations between target and realized harvest rates). In this way, we evaluated how robust the performances of the lower benchmarks were to violations in the base-case assumptions.

1.2 Candidate lower benchmarks

We evaluated lower benchmarks derived from previous management experience and the scientific literature (see Holt et al. 2009) on two classes of indicators: spawner abundances and fishing mortality relative to productivity. The benchmarks reflected a gradient in size from less precautionary (e.g., at low spawner abundances or high fishing mortality, where only very depleted CUs were classified in the red zone) to more precautionary (e.g., at high spawner abundances or low fishing mortality, where moderately depleted CUs were classified in the red zone) (Table 2).

Table 2. List of lower benchmarks evaluated in the simulation model for indicators on spawner abundances (left side) and fishing mortality (right side). Continued on next page.

Class of indicator: spawner abundances			Class of indicator: fishing mortality		
Lower benchmark		Label	Lower benchmark		Label
Spawner abundance at a % of recruitment MSY	10%	S at 10% of R_{MSY}	Fishing mortality at a % of F_{MSY}	50%	50% F_{MSY}
	20%	S at 20% of R_{MSY}		60%	60% F_{MSY}
	30%	S at 30% of R_{MSY}		70%	70% F_{MSY}
	40%	S at 40% of R_{MSY}		80%	80% F_{MSY}
	50%	S at 50% of R_{MSY}		90%	90% F_{MSY}
	60%	S at 60% of R_{MSY}		100%	F_{MSY}
	70%	S at 70% of R_{MSY}		110%	110% F_{MSY}
	80%	S at 80% of R_{MSY}		120%	120% F_{MSY}
	90%	S at 90% of R_{MSY}		130%	130% F_{MSY}
Spawner abundance at 50% of maximum recruitment		S at 50% of R_{MAX}		140%	140% F_{MSY}
40% of spawner abundance at MSY		40% of S_{MSY}		150%	150% F_{MSY}

Class of indicator: spawner abundances		Class of indicator: fishing mortality	
Lower benchmark	Label	Lower benchmark	Label
Spawner abundance that will result in recovery to S_{MSY} in one generation in the absence of fishing under equilibrium conditions	S_{gen}	Maximum ln(recruits/spawner)	F_{MAX}
		Median ln(recruits/spawner)	F_{MED}

1.3 Performance criteria

To evaluate performance of benchmarks according to the idealized assessment framework, we made assumptions about the information required at steps 1-4 (reference frame, goal/endpoint, time frame, and management action), which in reality should be provided by fisheries management (Table 1). For example, for lower benchmarks on spawner abundances, to estimate the probability of extirpation over the long term (the first performance criteria), we assumed a constant escapement policy equivalent to the lower benchmark and ran the simulation over 100 years. Similarly, to estimate the probability of extirpation for lower benchmarks on fishing mortality, we assumed a constant harvest rate policy equivalent to the benchmark over 100 years. To evaluate the probability of recovery to a target (the second performance criteria) for benchmarks on spawner abundances, we set population abundances to the lower benchmark at the beginning of the simulation, and instead of a constant escapement policy, we assumed no commercial or recreational fishing (e.g., fishing from test fisheries and by-catch from other fisheries only) over one (or three) generations (the constant escapement policy resulted in almost no recovery and therefore gave non-informative comparisons among benchmarks). To evaluate the probability of recovery to a target for benchmarks on fishing mortality, we assumed fishing mortality equivalent to the lower benchmark over the same time period.

Table 3 Information required to evaluate lower benchmarks in the idealized assessment framework (described in Table 1) on two criteria: probability of extirpation (columns 2 and 3) and probability of recovery (columns 4 and 5), and for two classes of indicators: those based on spawner abundances (columns 2 and 4) and based on fishing mortality relative to productivity (columns 3 and 5). Although information items 1-4 in the idealized assessment framework are the responsibility of management, we provide examples here to demonstrate the properties of candidate benchmarks.

	Criteria to evaluate benchmark			
	Probability of extirpation		Probability of recovery	
Information required to evaluate benchmark	Benchmark on spawner abundances	Benchmarks on fishing mortality	Benchmark on spawner abundances	Benchmarks on fishing mortality
1. Reference frame	Biological production		Biological production	
2. Goal or endpoint	Extirpation (<100 for each year in one generation)		S_{MSY}	
3. Time frame to achieve goal or endpoint	100 years		1 (or 3) generations	
4. Fishery management actions	Constant escapement policy equivalent to the lower benchmark	Constant harvest rate policy equivalent to the lower benchmark	Spawner abundances initialized at the lower benchmark. No targeted fishing in subsequent years	Constant harvest rate policy equivalent to the lower benchmark
5. Model relating current state to a future state	As described in the "operating" model		As described in the "operating" model	
6. Deterministic upper benchmark	NA		NA	
7. Deterministic lower benchmark	As described in Table 2		As described in Table 2	
8. Incorporate uncertainty into lower benchmark	As described in the "operating" model		As described in the "operating" model	
9. Choice of risk tolerance	A risk classification scheme was adapted from DFO's Fishery Decision-Making Framework Incorporating the Precautionary Approach (2009). Further work is required to identify risk tolerances from stakeholders.			

2. METHODS

2.1 Simulation models to evaluate lower benchmarks

We developed two simulation models to evaluate candidate lower benchmarks on the two performance criteria: one model that evaluated the probability of extirpation over the long term (100 years) (Model 1), and one model that evaluated the probability of recovery to a target over one (or three) generations (Model 2). We describe Model 1 in Sections 2.1.1 to 2.1.4, and then describe how Model 2 differs from Model 1 in Section 2.1.5. All variables and parameters are defined in Table 4. Model 1 had four components: a population dynamics sub-model (Box 1 of Figure 1a), an observation sub-model (Box 2), a management sub-model (Box 3), and a performance module (Box 4). The population dynamics, observation, and management sub-models were repeated over 100 years and 500 Monte Carlo trials (the number required to stabilize output metrics).

Table 4. Parameters and variables used to simulate population dynamics, observations, and management for the base case model.

Equation where parameter or variable is first introduced	Parameter or variable	Definition	Value (for estimated parameters only)
1	y	Brood year	
	R	Abundance of recruitment	
	S	Abundance of spawners	
	a	Productivity parameter of Ricker model	
	b	Capacity parameter of Ricker model	
	φ	Autocorrelated stochastic variability in recruitment	
	ρ	Autocorrelation coefficient	0.37
	ν	Stochastic deviations in recruitment	
	σ^2_ν	Variance in residual error of spawner-recruitment relationship	0.68

Equation where parameter or variable is first introduced	Parameter or variable	Definition	Value (for estimated parameters only)
2	R_{dep}	Recruitment at low spawner abundances accounting for depensatory mortality	
	S^*	Threshold in spawner abundances below which depensatory mortality occurs	
6	G	Total number of classes of age-at-maturity	3
	g	Age-at-maturity	
	t	Return year	
	$p_{g,t}$	Proportion of recruits that return at a given age in a given year	
	$x_{g,t}$	Dummy variable calculated in Eqn. 4	
7	$\overline{p}_g$	Average proportion of recruits that return at age g	$p_1 = 0.003$, $p_2 = 0.917$, $p_3 = 0.081$
	ϖ	Standard deviation in the multivariate logistic distribution of proportions at age	0.1
	ε	Standard normal deviates	
8	R_O	Observed recruitment	
	t	Return year	
	κ	Normally distributed random variability	
	σ_κ^2	Variance in κ	0.19
9	h_t	Target harvest rate in return year t	
	E_t	Escapement goal in year t	
10	F_L	Lower benchmark on fishing mortality	
In text		Standard deviation between realized and target harvest rate	0.19

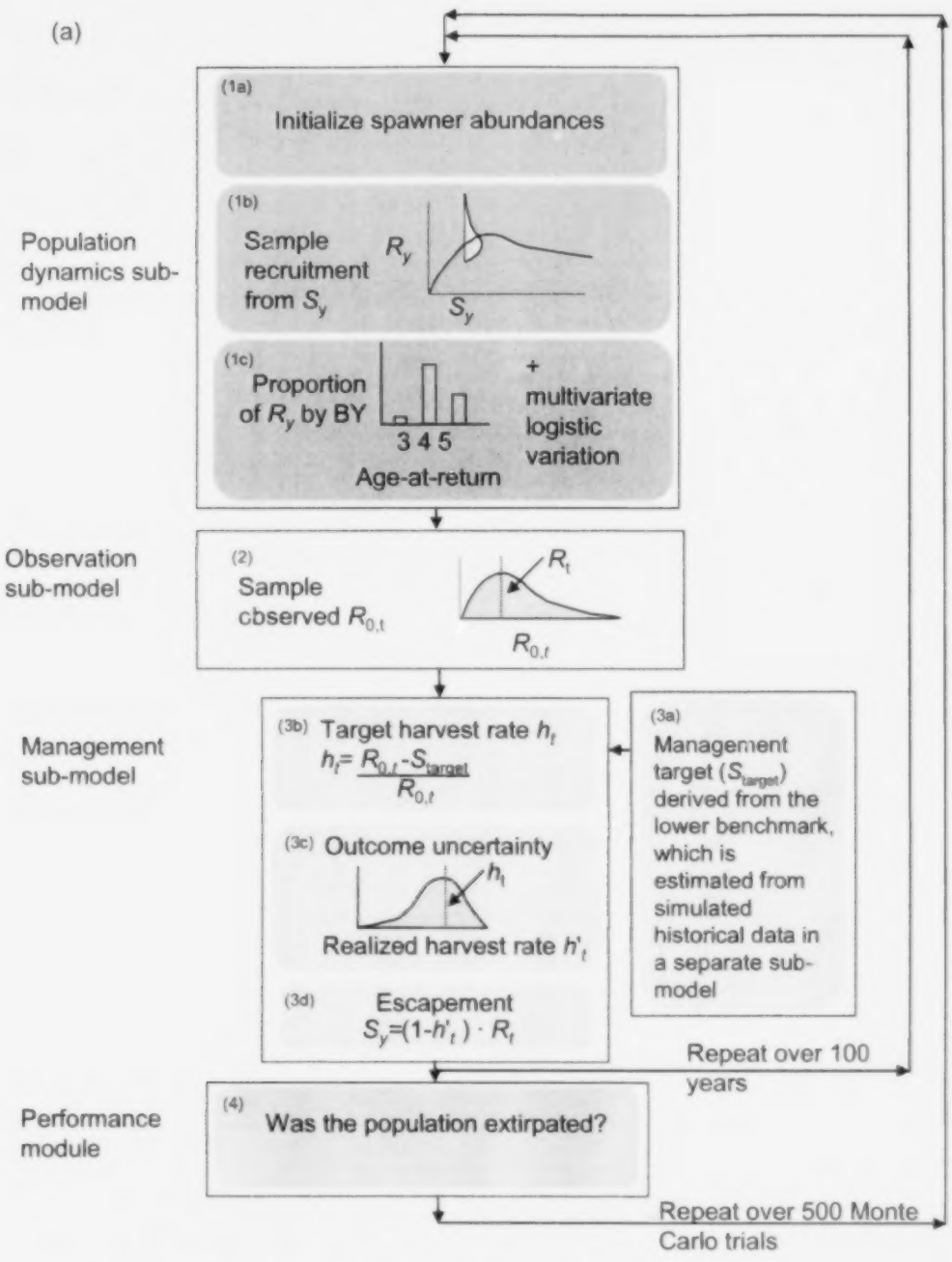
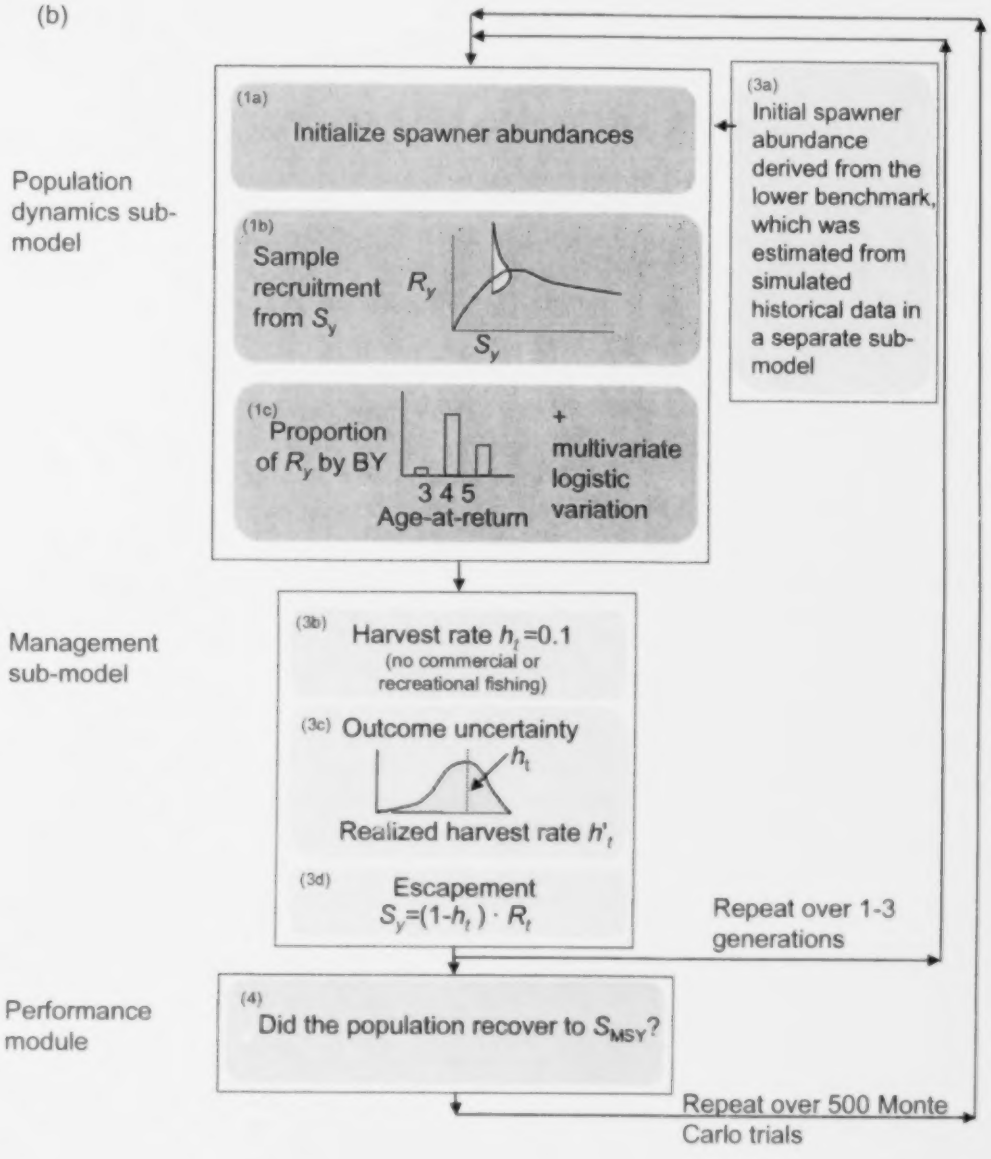


Figure 1. Simulation modelling framework used to evaluate the probability of extirpation over the long term (a) and probability of recovery to S_{MSY} (b, next page) for lower benchmarks on spawner abundances. S_y is the spawner abundance in brood year y, R is recruitment, t is year of recruitment, R_0 is observed recruitment, h is target harvest rate derived from target spawner abundances, S_{target}, and observed recruitment, and h' is the realized harvest rate (i.e., harvest with outcome

uncertainty). Note, panel (b) does not include an "Observation sub-model" because for that model evaluated probability of recovery under a scenario of no directed fishing, and so observations of abundance were not required.



2.1.1 Population dynamics sub-model

In the population dynamics sub-model, we simulated numerous hypothetical sockeye salmon populations, incorporating stochastic variability in recruitment and age-at-maturity. Specifically, spawner abundance in brood year y, S_y, was used to calculate

recruitment resulting from that spawning, R_y, using a Ricker model with lognormally distributed random variation, and autocorrelation in residuals with a one-year time lag:

(Eqn. 1) $$R_y = S_y e^{a(1-S_y/b)+\varphi_y}, \quad \varphi_y = \rho\varphi_{y-1} + \nu_y, \quad \nu \sim N\left(0, \sigma_\nu^2\right),$$

where a is the productivity parameter ($\log_e$ (recruits/spawner) at low spawner abundances), b is spawner abundances at replacement (or equilibrium), φ describes autocorrelated variability in recruitment, ρ is the autocorrelation coefficient, and ν describes the stochastic deviations in recruitment.

We included depensatory mortality at low abundances as described in Holt (2007). Below a lower threshold (S^* = 500 spawners), recruitment that accounted for depensation ($R_{dep,y}$) declined more rapidly as spawner abundances declined than if depensation was ignored (i.e., when R_y was derived from Eqn. 1):

(Eqn. 2) $$R_{dep,y} = R_y \cdot \left(1 - \sqrt{\frac{S^* - S_y}{S^*}}\right), \text{ for } S_y < S^*$$

Those reductions in recruitment were curvilinear with steepest rates of change immediately below S* and an asymptote near zero spawners (of zero recruits). Although evidence for depensatory mortality at low abundances is weak for most species and stocks of Pacific salmon, it has been documented at abundances higher than 500 spawners (our threshold, S^*) in some cases (e.g., 7000 spawners, Cultus Lake sockeye salmon, M. Bradford, pers. comm. Cooperative Resource Management Institute, Simon Fraser University, Burnaby, B.C.). We therefore varied the lower threshold below which depensation occurred in a sensitivity analysis. An alternative approach to modelling depensation is to offset the spawner-recruitment model to the right by the abundance of spawners below which depensatory mortality results in zero recruitment (Chen et al., 2002). However, in contrast to the approach described in Eqns. (1) and (2), for the method of Chen et al. (2002), the predicted recruitment above the depensation threshold (or offset amount) varies depending on whether depensation at low spawner abundances is accounted for or ignored. To isolate the effects of depensation at low spawners only, we used the method described in Eqns. (1) and (2). The assumptions associated with the base case and all sensitivity analyses are described in Table 5.

Table 5. Assumptions of the "base-case" model, and variations to those assumptions applied in the sensitivity analyses. "Sub-model" pertains to where that assumption is made in the operating model, as described in Figure 1. Note, some sensitivity analyses were performed on only a subset of model scenarios (e.g., the last sensitivity analysis was performed only on benchmarks of spawner abundances, because for benchmarks based on fishing mortality, management actions were derived from pre-specified F values). Continued on next page.

Assumption	**Sub-model (Eqn.)**	**"Base case"**	**Variations applied to sensitivity analyses**
Threshold in spawner abundance below which depensatory mortality occurs	Population dynamics sub-model (Eqn. 2)	500	1000, 7000
Form of the stock-recruitment model	Population dynamics sub-model (Eqns. 1-5)	Ricker with autocorrelation and depensation	Ricker without autocorrelation and depensation, Beverton-Holt, Larkin
Productivity (Ricker a parameter = $\log_e(R/S)$ at low S)	Population dynamics sub-model (Eqn. 1)	Moderate (a = 1.5, 4.5 R/S at low S)	Low (a = 0.5, or 1.6 R/S), High (a = 2.0, or 7.4 R/S)
Time trends in productivity (Ricker a parameter= $\log_e(R/S)$ at low S)	Population dynamics sub-model (Eqn. 1)	Constant productivity over time	Linear increase in productivity equivalent to 0.01 $\log_e(R/S)$ per year, linear decline in productivity equivalent to 0.015 $\log_e(R/S)$ per year, cyclic trend in productivity with a period of 20 years and amplitude of 0.5 $\log_e(R/S)$
Magnitude of observation errors (σ_κ)	Observation sub-model (Eqn. 8)	Low (σ_κ= 0.19)	High (σ_κ= 0.38)
Length of time series used to estimate stock-recruitment model parameters and benchmarks	Management sub-model	20	15, 30

Assumption	Sub-model (Eqn.)	"Base case"	Variations applied to sensitivity analyses
Magnitude of outcome uncertainties	Management sub-model	High (standard deviation = 0.19)	Low (standard deviation = 0.097)
Lower limit on fishing mortality (due to non-commercial harvest, such as by-catch)	Management sub-model	0.1	0.02, 0.2

For some stocks and species, alternative formulations of the spawner-recruitment relationship may be appropriate (e.g., Ricker without depensation or autocorrelation, (Eqn. 3), Beverton-Holt (Eqn. 4), or Larkin models (Eqn. 5)). We therefore varied the stock-recruitment model in a sensitivity analysis.

(Eqn. 3) $$R_y = S_y e^{a'(1-S_y/b')+v_y},\ v \sim \mathrm{N}\left(0,\sigma_v^{\,2}\right)$$

(Eqn. 4) $$R_y = \frac{S}{a'' \cdot S + b''} \cdot e^{v},\ v \sim \mathrm{N}\left(0,\sigma_v^{\,2}\right)$$

(Eqn. 5) $$R_y = S_y e^{\left(a''' + b_1''' S_y + b_2''' S_{y-1} + b_3''' S_{y-2}\right) + v_y},\ v \sim \mathrm{N}\left(0,\sigma_v^{\,2}\right)$$

where a', b', a'', b'', a''', b_1''', b_2''', and b_3''' are parameters. The values of those parameters were selected so that S_{MSY} and harvest rate at *MSY* for each model were equivalent to those for the base-case Ricker model.

We assumed the productivity parameter of the stock-recruitment relationship was constant over time, but included normally distributed variability in that parameter over Monte Carlo trials (mean a=1.5, equivalent to approximately 4.5 recruits/spawners at low spawners, sd =0.3). In a sensitivity analyses, we investigated the effects of constant low productivity (mean a = 0.5, or 1.6 recruits/spawner) and high productivity (mean a = 2.0, or 7.4 recruits/spawner) on the relative performance of benchmarks. We further investigated the effects of three time trends in productivity: a linear increase, a linear decrease, and a sinusoidal pattern with a period of 20 years and amplitude of 1.0 $\log_e$(recruits/spawner). We varied the spawner abundances at equilibrium (b parameter) in fixed intervals of 1000 spawners between 1000 and 100 000 fish (i.e., the model was run separately for populations of different carrying capacities). This allowed us to compare results under various combinations ((3+3) × 100 = 600) of productivity (a) and spawner abundances at equilibrium (b).

Natural variation in the proportion at each age-at-maturity p_g, in return year t, was incorporated into the population dynamics model using a multivariate logistic distribution (Schnute and Richards, 1995):

(Eqn. 6) $$p_{g,t} = \frac{e^{x_{g,t}}}{\sum_{g=1}^{G} e^{x_{g,t}}},$$

where,

(Eqn. 7) $$x_{g,t} = \log_e(\bar{p}_g) + \varpi\varepsilon_{g,t} - \frac{1}{G}\sum_{g=1}^{G}\left[\log_e(\bar{p}_g) + \varpi\varepsilon_{g,t}\right],$$

G is the oldest age class, $\bar{p}_g$ is the mean proportions at age, ϖ is the standard deviation in the multivariate logistic distribution of proportions at age, and $\varepsilon_{g,t}$ are standard normal deviates. Both $\bar{p}_g$ and ϖ were estimated from historical data (described in the Model Parameterization sub-section below). Spawner abundances were initialized at 1000 spawners.

2.1.2 Observation sub-model

Uncertainty in observations of recruitment come from many sources, including errors in visual observations of spawner abundance (e.g., visual observations from stream walks or aerial surveys), sampling variability of spawners and catches, and uncertainty in non-harvest mortality during return migration. The observed number of recruits, R_0, in year t, was calculated from the true number of recruits, R_t, with multiplicative, lognormally distributed random variability, as in (Cass et al., 2003),

(Eqn. 8) $$R_{0,t} = R_t e^{\kappa_t},\ \kappa \sim \mathrm{N}\left(0, \sigma_\kappa^{\,2}\right),$$

where κ is normally distributed random variability with a standard deviation, σ_κ.

To properly parameterize natural process variation in recruitment (ν) (Eqn. 1) and observation error (κ) (Eqn. 8), we needed to partition variability from those two specific sources from the total observed variability in recruitment. Historical recruitment data used to estimate parameters in equation 1 contained both natural process variation and observation error; hence recruitment calculated from these equations also contained both ν and κ. To separate the various contributors to total variability, we used a simple simulation model to estimate the standard deviations of the natural process variation, σ_ν (equations 1), which, in combination with observation errors (κ), resulted in standard deviations in total recruitment equal to those observed historically (σ_ψ). Note that those variances were not additive (i.e., $\sigma_\psi^{\,2} \neq \sigma_\nu^{\,2} + \sigma_\kappa^{\,2}$), indicating that the sources of variability were not independent. We found that the total combined uncertainty (ψ) was swamped by large natural variability in recruitment. Specifically, the standard deviation in natural process

variation was equal to 94% of the standard deviation in total combined recruitment for both stocks (i.e., $\sigma_v = 0.94\sigma_\psi$).

2.1.3 Management sub-model

Management actions were simulated in two parts, (1) the selection of a management target based on a constant escapement policy equivalent to the lower benchmark on spawner abundances or constant harvest rate equivalent to the lower benchmark on fishing mortality (Table 2), and (2) the implementation of that target including outcome uncertainty, i.e., uncertainty in the outcomes of implementing a harvest strategy (Holt and Peterman, 2006).

Benchmarks related to S_{MSY} or F_{MSY} cannot be estimated exactly due to observation errors in abundances, sampling variability, and model misspecification, among other factors. To account for those uncertainties, we identified benchmarks using parameter estimates of the spawner-recruitment relationship derived from simulated historical data. Specifically, for every Monte Carlo trial in the overall simulation model, we simulated 20 years of historical data in a separate sub-model (i.e., separate from the models used to evaluate lower benchmarks) assuming a Ricker spawner-recruitment with the same parameters used in the population dynamics sub-model for that Monte Carlo trial, and a harvest rate of 70% (to represent a heavily exploited stock) with beta-distributed variability in outcomes (Box 3a, Fig. 1). Maximum likelihood techniques were then used to estimate parameters of the Ricker spawner-recruitment relationship (a, b and σ^2_v), as well as the lower benchmark. By using short time-series of simulated data to estimate parameters, we were able to produce the commonly observed positive bias in productivity (Walters and Martell, 2004). In a sensitivity analysis, we increased the number of years of data simulated to estimate parameters from 20 to 30 in order to evaluate the effects of increased historical information on the performance of benchmarks.

To improve estimation of the capacity parameter ("b" of the stock-recruitment relationship), we included prior information on that parameter, which, in practice, can be generated from freshwater capacity studies or landscape characteristics (Parken et al., 2006; Shortreed et al., 2001). Specifically, a penalty was added to the likelihood function, which was drawn from a log-normal distribution with a mean equal to the true value and a standard deviation of 0.6, in units of $\log_e$(1000 spawners). Estimates of "b" that were far from the true value were penalized inversely proportional to that distribution.

For lower benchmarks on spawner abundances, target harvest rates in return year t, h_t, were calculated from observed recruitment, $R_{O,t}$, and the escapement goal, E_t,

(Eqn. 9) $$h_t = 1 - E_t / R_{O,t} \ .$$

For lower benchmarks on fishing mortality, F_L, target harvest rates were calculated using the standard equation to convert natural logarithms (F) to a proportion between 0 and 1 (h):

(Eqn. 10) $$h_t = 1 - e^{-F_L} \ .$$

Target harvest rates are rarely achieved exactly because of variability in the catchability of fish, non-compliance to fishing regulations, and management pressures that cause decisions to deviate from those that achieve targets, among other factors (Holt et al. 2006). To account for those uncertainties, we included random variation in the outcomes of harvest rates assuming a beta-distribution of errors (as described in Holt and Peterman (2008)).

2.1.4 Performance module

In the performance module, we evaluated the probability of extirpation (i.e., populations where spawner abundances < 100 fish in four consecutive years) by computing the proportion of Monte Carlo trials where populations met that criterion.

2.1.5 Differences between Models 1 and 2

The model used to evaluate probability of recovery to a target (Model 2) differed from Model 1 in four ways. First, the spawner abundances at equilibrium was set to a single value, 10,000 spawners instead of multiple values between 1000 and 100,000, because preliminary results suggested that probability of recovery was independent of spawner abundances at equilibrium. Second, for candidate benchmarks on spawner abundances, spawners were initialized at the lower benchmark instead of 1000 fish so that the recovery from the lower benchmark could be evaluated. For candidate benchmarks on fishing mortality, spawners were instead initialized at 10% of spawner abundances at equilibrium. Third, for candidate benchmarks on spawner abundances, we assumed no commercial or recreational fishing. We assumed the unavoidable harvest (e.g., due to test fisheries and by-catch from other fisheries, among other sources), h_t, was 0.1, but this value was varied in a sensitivity analysis, h_t= 0.02 and h_t= 0.2. Although those harvest rates are not management targets, we included outcome uncertainty in those values to simulate interannual variability in non-commercial, non-recreational harvest. For candidate benchmarks on fishing mortality, the target harvest rate was set to the lower benchmark on fishing mortality and also included outcome uncertainty. Fourth, in the performance module, we evaluated the probability of recovery to S_{MSY} in one and three generation(s), instead probability of extirpation over 100 years, by computing the proportion of Monte Carlo trials where populations rebuilt to above S_{MSY} in at least one year over that time period.

2.2 Model parameterization

The parameters in Equations 1, 6, and 7 were estimated from historical data on Early Stuart sockeye salmon (K. Benner, pers. comm., Fisheries and Oceans Canada, 985 McGill Place, Kamloops, B.C., V2C 6X6) (Table 4), with the exception of the productivity and capacity parameters ("a" and "b") in Equation 1, which are as described in the "Population dynamics sub-model" and "Observation sub-model" sub-sections. Although our base-case represents one species in one region (sockeye salmon in the Fraser River) our extensive sensitivity analyses cover characteristics of stocks and species with alternative stock-recruitment relationships (e.g., models with and without depensation and

autocorrelation, Beverton-Holt model, and Larkin model) and scenarios about observations, assessments, and management.

The magnitude of observation errors was derived from mark-recapture studies on sockeye spawner abundances in Chilko Lake between 2001 and 2004 (T. Whitehouse pers. comm. Fisheries and Oceans Canada, 985 McGill Place, Kamloops, B.C., V2C 6X6) (standard deviation in observation error, σ_K, = 0.19). Although uncertainties in catch estimates and non-harvest mortality are not included in that estimate, we increased σ_K in a sensitivity analysis to twice that value (σ_K = 0.38), a rough upper estimate of the magnitude of the total observation errors in recruitment.

Parameters describing outcome uncertainty were for Summer-Run sockeye salmon on the Fraser River, as estimated by Holt and Peterman (2006) (standard deviation between realized and target mortality rates = 0.097). In a sensitivity analysis, we increased the magnitude of those uncertainties to those observed for Late-Summer run sockeye (standard deviation = 0.19) (Holt and Peterman, 2006), a stock with relatively large deviations between target and realized mortality rates.

3. RESULTS

First we present results on Model 1 (the probability of extirpation over the long term) and then Model 2 (the probability of recovery to S_{MSY} within one (or three) generations). Within each model, we first evaluate lower benchmarks on spawner abundances, and then lower benchmarks on fishing mortality.

3.1 Model 1: Probability of extirpation over the long term

3.1.1 Lower benchmarks on spawner abundances

When populations were projected forward under constant escapement policies equivalent to lower benchmarks derived from S at 40-90% of R_{MSY} (black lines labeled 40-90% Figure 2), S at 50% of R_{MAX} (red line), 40% of S_{MSY} (blue line), and S_{gen} (green line), probabilities of extirpation were low or very low (probabilities <25% or <5%, respectively, definitions adapted from DFO's "Fishery decision-making framework incorporating the Precautionary Approach"(2009)) when equilibrium abundances were > 15,000 fish (right side of Figure 2). Below that equilibrium abundance (left side of Figure 2), probabilities of extirpation were higher or rose steeply for all benchmarks. When we assumed populations were highly productive (mean Ricker "a" value = 2.0, equivalent to 7.4 recruits/spawner at low spawner abundances), probabilities of extirpation tended to be lower for most benchmarks (Figure 3c) compared with the moderate productivity case (Figure 3b). In other words, highly productive populations were better able to rebound from occasional poor recruitment years than less-productive populations. In contrast, when we assumed populations were relatively unproductive (mean Ricker "a" value = 0.5, equivalent to 1.6 recruits/spawner and low spawner abundances), probabilities of extirpation tended to be higher for most benchmarks. The differences among productivity scenarios were relatively

minor for the benchmark based on S_{gen}, spawner abundances that will result in recovery to S_{MSY} in one generation under equilibrium conditions (green line; i.e., performance of S_{gen} was relatively insensitive to variability in productivity levels). Those differences were relatively large for benchmarks based on R_{MSY} (black lines) and S_{MSY} (blue line). For the remaining sensitivity analyses, we show results for only a single benchmark, S_{gen}. The trends in results (direction of change and rank sensitivity of performance to the assumption) were similar among benchmarks.

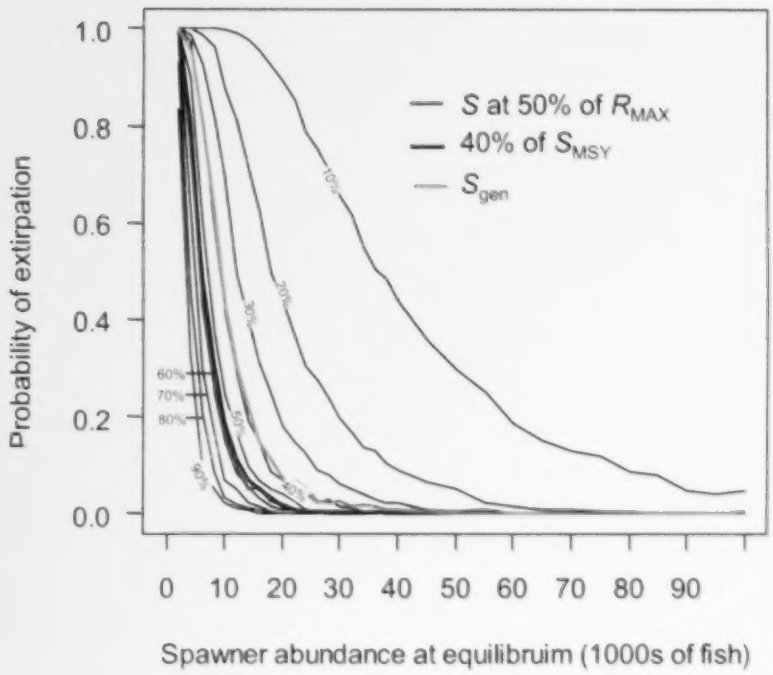


Figure 2. Probabilities of extirpation over the long term (100 years) for simulated populations of Pacific salmon under a constant escapement policy equal to the lower benchmarks derived from spawner abundances at various percentages of R_{MSY} (black lines) over a gradient in equilibrium stock sizes (X-axis). Three other lower benchmarks are shown: spawner abundances, S, at 50% of R_{MAX} (red line), 40% of S_{MSY} (blue line), and spawner abundance resulting in recovery to S_{MSY} in one generation without fishing under equilibrium conditions, S_{gen} (green line).

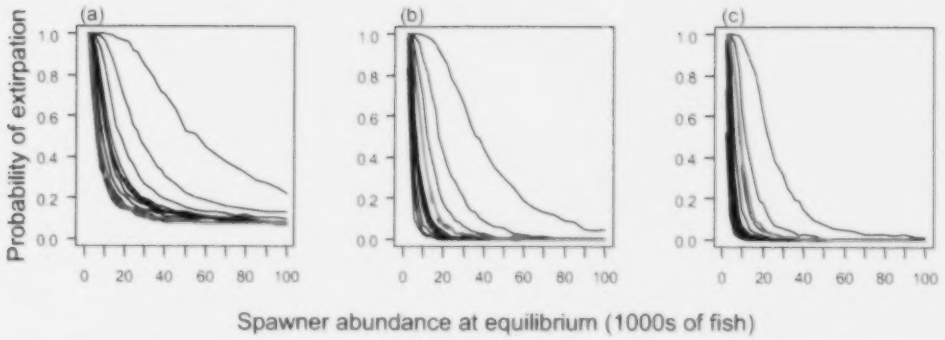


Figure 3. Probabilities of extirpation, p, over the long term (100 years) for unproductive (mean Ricker "a" parameter = 0.5, or 1.7 recruits/spawner at low spawner abundances) (a), moderately productive (mean Ricker "a" parameter = 1.5, or 4.5 recruits/spawner at low spawner abundances) (b), and highly productive (mean Ricker "a" parameter = 2.0, or 7.4 recruits/spawner at low spawner abundances) (c) simulated populations of Pacific salmon under a constant escapement policy equal to the lower benchmarks derived from spawner abundances at various percentages of R_{MSY} (black lines, ranging from 10% (top line) to 90% (bottom line)) over a gradient in equilibrium stock sizes (X-axis). Three other lower benchmarks are shown, as described in the caption to Fig.2: S at 50% of R_{MAX} (red line), 40% of S_{MSY} (blue line), and S_{gen} (green line).

Similar to the results from different constant levels of productivity, when productivity increased over time, the probability of extirpation declined, and vice versa (Figure 4). When cyclic patterns in recruitment were introduced into the operating model (with mean Ricker "a" parameter = 1.5), probability of extirpation declined only marginally.

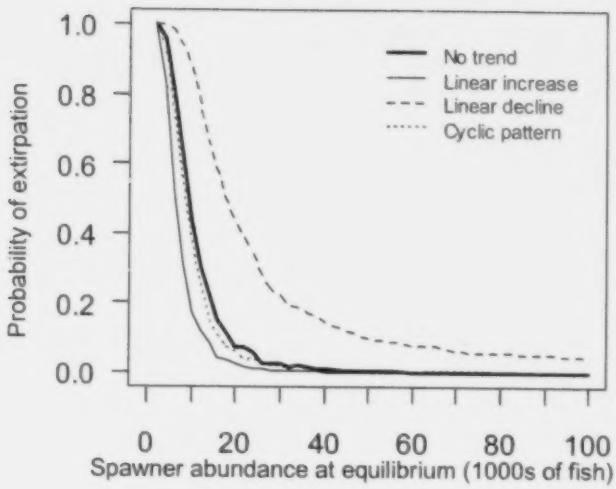


Figure 4. Probabilities of extirpation over the long term (100 years) for simulated populations of Pacific salmon under a constant escapement policy equal to the lower benchmark derived from S_{gen} (spawner abundances that will result in recovery to S_{MSY} in one generation under equilibrium conditions) and four assumptions about the trends in stock productivity (Ricker "a" parameter): no trend (thick solid line); linear increase over time (thin solid line); linear decline over time (dashed line); and cyclic pattern (dotted line), over a gradient in equilibrium stock sizes (X-axis).

Probabilities of extirpation were higher for the Ricker model with autocorrelated errors and depensatory mortality than for the remaining models: standard Ricker without autocorrelation and depensation, Beverton-Holt, and Larkin (Figure 5). We assumed recruitment followed a Ricker model with autocorrelation and depensation for the base case because of empirical evidence for those phenomena (Chen et al., 2002; Korman et al., 1995; Wood, 1987), and to generate a precautionary evaluation of performance (i.e., an upper estimate of probability of extirpation). When we increased the threshold below which depensation occurred to 7000, the probabilities of extirpation increased to near 100% (Figure 6). Populations were initialized at 1000 spawners in our simulation model and were unable to rebuild from low abundances under that scenario.

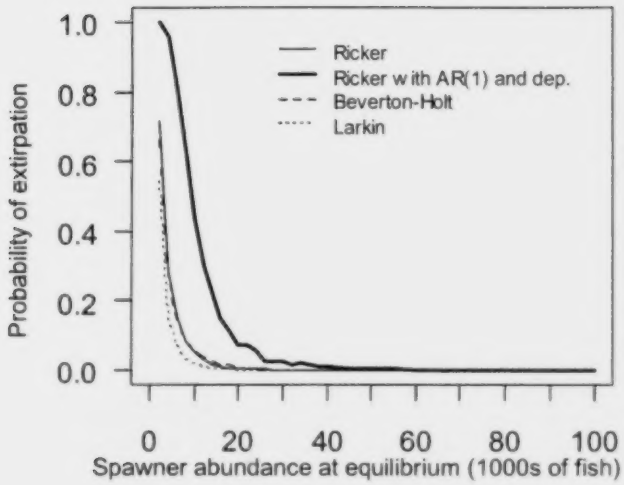


Figure 5. Probabilities of extirpation over the long term (100 years) for simulated populations of Pacific salmon under a constant escapement policy equal to the lower benchmark derived from S_{gen} (spawner abundances that will result in recovery to S_{MSY} in one generation under equilibrium conditions) and four assumptions about the stock-recruitment model: Ricker model (thin solid line), Ricker model with autocorrelation and depensatory mortality at low spawner abundances (thick solid line), Beverton-Holt model (dashed line), and Larkin model (dotted line), over a gradient in equilibrium stock sizes (X-axis).

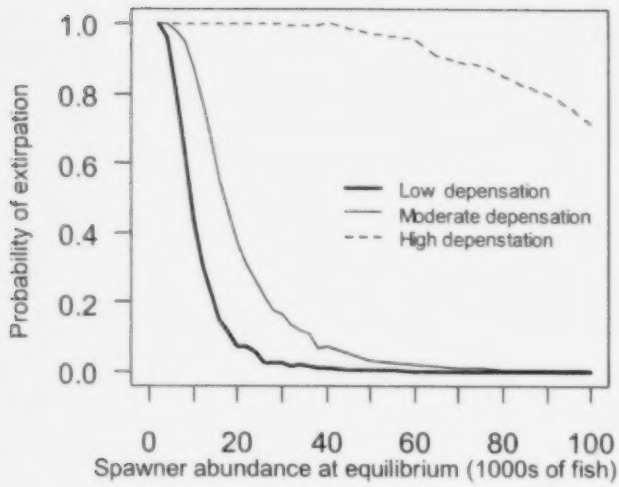


Figure 6. Probabilities of extirpation over the long term (100 years) for simulated populations of Pacific salmon under a constant escapement policy equal to the lower benchmark derived from S_{gen} (spawner abundances that will result in recovery to S_{MSY} in one generation under equilibrium conditions) and three assumptions about the spawner abundance below which depensatory mortality occurs: 500 fish (thick solid line); 1000 fish (thin solid line); 7000 (dashed line), over a gradient in equilibrium stock sizes (X-axis).

Probabilities of extirpation were less sensitive to variability in management parameters (the magnitude of observation errors and outcome uncertainties, the number of years of historical data available to estimate benchmarks, and the lower limit on harvest rates due to non-commercial and non-recreational catch) than to biological parameters on productivity. In general, increasing uncertainty and harvest resulted in increasing probability of extirpation (Figure 7, Figure 8, Figure 9, and Figure 10).

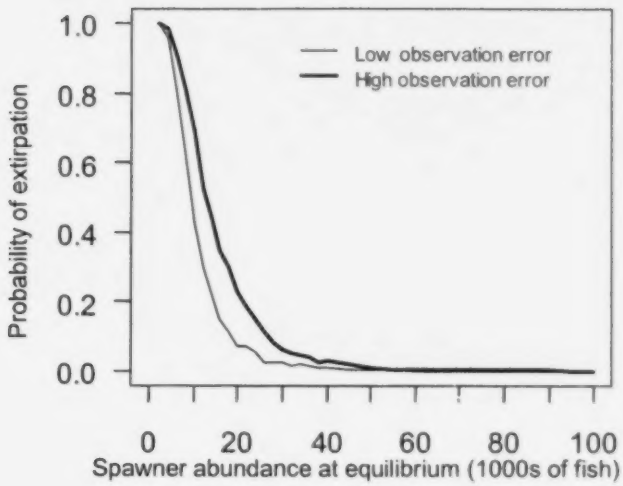


Figure 7. Probabilities of extirpation over the long term (100 years) for simulated populations of Pacific salmon under a constant escapement policy equal to the lower benchmark derived from S_{gen} (spawner abundances that will result in recovery to S_{MSY} in one generation under equilibrium conditions) and two assumptions about the magnitude of observation errors: standard deviation between actual and observed abundance = 0.19 (thin solid line) and 0.38 (thick solid line), over a gradient in equilibrium stock sizes (X-axis).

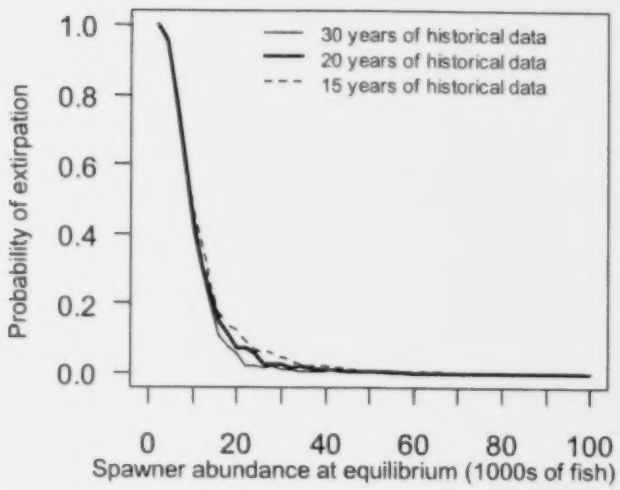


Figure 8. Probabilities of extirpation over the long term (100 years) for simulated populations of Pacific salmon under a constant escapement policy equal to the lower benchmark derived from S_{gen} (spawner abundances that will result in recovery to S_{MSY} in one generation under equilibrium conditions) and three assumptions about the number of years of historical data used to estimate R_{MSY} when deriving the lower benchmark (corresponding to the magnitude of assessment uncertainty): 30 years (low assessment uncertainty, thin solid line), 20 years (moderate assessment uncertainty, thick solid line), and 15 years (high assessment uncertainty, dashed line), over a gradient in equilibrium stock sizes (X-axis).

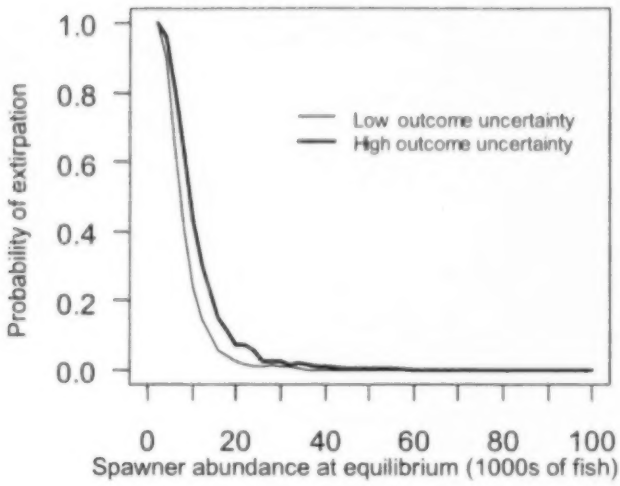


Figure 9. Probabilities of extirpation over the long term (100 years) for simulated populations of Pacific salmon under a constant escapement policy equal to the lower benchmark derived from S_{gen} (spawner abundances that will result in recovery to S_{MSY} in one generation under equilibrium conditions) and two assumptions about the magnitude of outcome uncertainty: standard deviation between realized harvest rates and targets = 0.097 (thin solid line) and 0.19 (thick solid line), over a gradient in equilibrium stock sizes (X-axis).

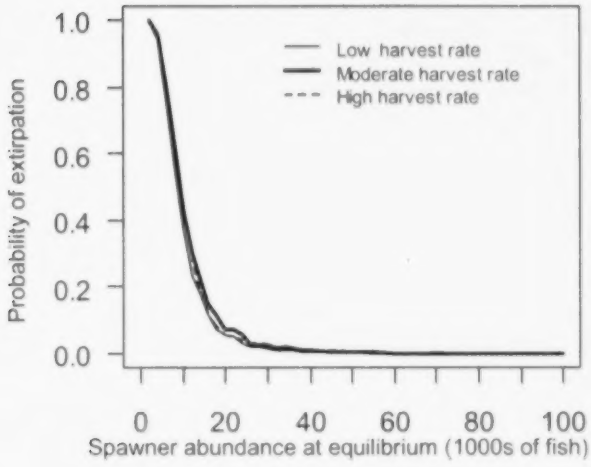


Figure 10. Probabilities of extirpation over the long term (100 years) for simulated populations of Pacific salmon under a constant escapement policy equal to the lower benchmark derived from S_{gen} (spawner abundances that will result in recovery to S_{MSY} in one generation under equilibrium conditions) and three assumptions about the lower limit on harvest rate, h_l, (due to non-target fishing mortality, e.g., test-fishery and by-catch): low h_l = 0.02 (thin solid line), moderate h_l = 0.1 (thick solid line), and high h_l = 0.2 (dashed line), over a gradient in equilibrium stock sizes (X-axis).

3.1.2 Lower benchmarks on fishing mortality

When populations were subjected to fishing mortalities equivalent to lower benchmarks on F that were between 50-110% of F_{MSY}, the probabilities of extirpation were low or very low (probabilities <25% or <5%, respectively) for populations with equilibrium abundances greater than 30,000 spawners. In contrast, when fishing mortality was equal to benchmarks derived from 120-150% of F_{MSY}, F_{MAX}, and F_{MED}, the probabilities of extirpation were moderately low (probabilities 25-50%) or moderately high (probabilities >50%). Performances of benchmarks near F_{MSY} (90%-110% of F_{MSY}) (red line, and black lines directly above and below red line) were least sensitive to variability in productivity; performances of benchmarks derived from F_{MAX} and F_{MED}, (blue and green lines, respectively) were most sensitive (Figure 12). For subsequent sensitivity analyses, we show results for the lower benchmark, F_{MSY}, only. The trends in results (direction of change and rank sensitivity of performance to the assumption) were similar among benchmarks.

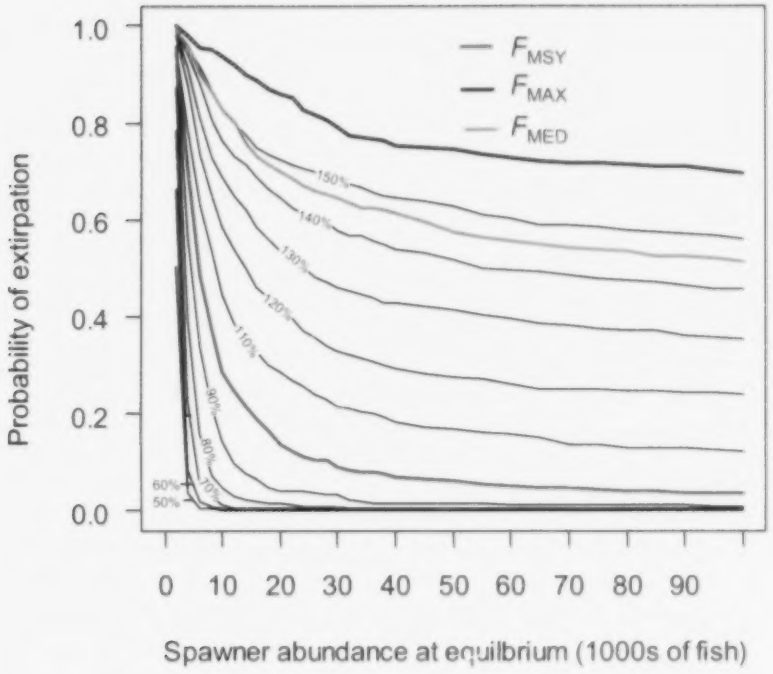


Figure 11. Probabilities of extirpation over the long term (100 years) for simulated populations of Pacific salmon under a constant fishing mortality rate policy equal to the lower benchmarks derived from various percentages of F_{MSY} (black lines) over a gradient in equilibrium stock sizes (X-axis). Three other lower benchmarks are shown: F_{MSY} (red line, equivalent to 100% F_{MSY}), the maximum $\log_e$(recruits/spawner) at low spawner abundances (i.e., Ricker "*a*" parameter) (F_{MAX}, blue line), and the median $\log_e$(recruits/spawner) (F_{MED}, green line).

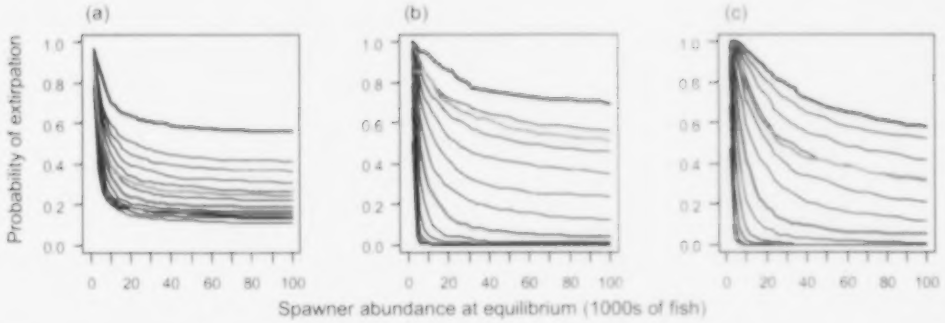


Figure 12. Probabilities of extirpation, p, over the long term (100 years) for unproductive (mean Ricker "a" parameter = 0.5, or 1.7 recruits/spawner at low spawner abundances) (a), moderately productive (mean Ricker "a" parameter = 1.5, or 4.5 recruits/spawner at low spawner abundances) (b), and highly productive (mean Ricker "a" parameter = 2.0, or 7.4 recruits/spawner at low spawner abundances) (c) simulated populations of Pacific salmon under a constant escapement policy equal to the lower benchmarks derived from various percentages of F_{MSY} (black lines, ranging from 150% (top line) to 50% (bottom line)) over a gradient in equilibrium stock sizes (X-axis). Three other lower benchmarks are shown, as described in the caption to Fig.11: F_{MSY} (red line), F_{MAX} (blue line), and F_{MED} (green line).

Similar to the results for benchmarks on spawner abundances, probabilities of extirpation for benchmarks on fishing mortality were less sensitive to variability in management parameters (the magnitude of outcome uncertainties and the number of years of historical data available to estimate benchmarks) than to biological parameters on productivity (e.g., especially large increases and declines over time) (Figure 13, Figure 14, and Figure 15). In general, increasing uncertainty and harvest resulted in increasing probability of extirpation (Figure 16 and Figure 17).

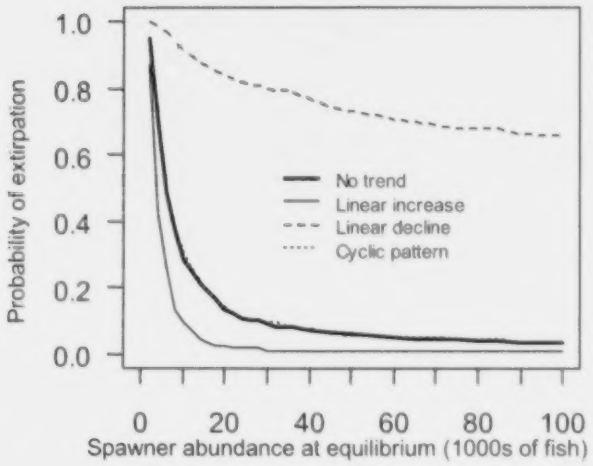


Figure 13. Probabilities of extirpation over the long term (100 years) for simulated populations of Pacific salmon under a constant fishing mortality rate policy equal to the lower benchmarks, F_{MSY}, and four assumptions about the trends in stock productivity (Ricker "*a*" parameter): no trend (thick solid line); linear increase over time (thin solid line); linear decline over time (dashed line); and cyclic pattern (dotted line), over a gradient in equilibrium stock sizes (X-axis).

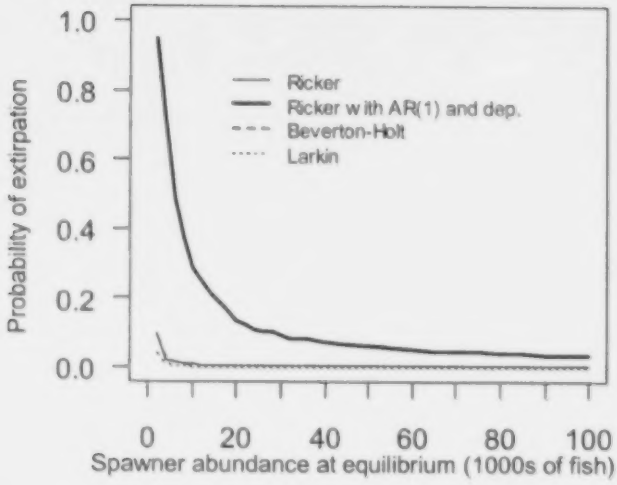


Figure 14. Probabilities of extirpation over the long term (100 years) for simulated populations of Pacific salmon under a constant fishing mortality rate policy equal to the lower benchmarks, F_{MSY}, and four assumptions about the stock-recruitment model: Ricker model (thin solid line), Ricker model with autocorrelation and depensatory mortality at low spawner abundances (thick solid line), Beverton-Holt model (dashed line), and Larkin model (dotted line), over a gradient in equilibrium stock sizes (X-axis). Lines for the Ricker, Beverton-Holt, and Larkin models lie almost on top of each other near the bottom X-axis.

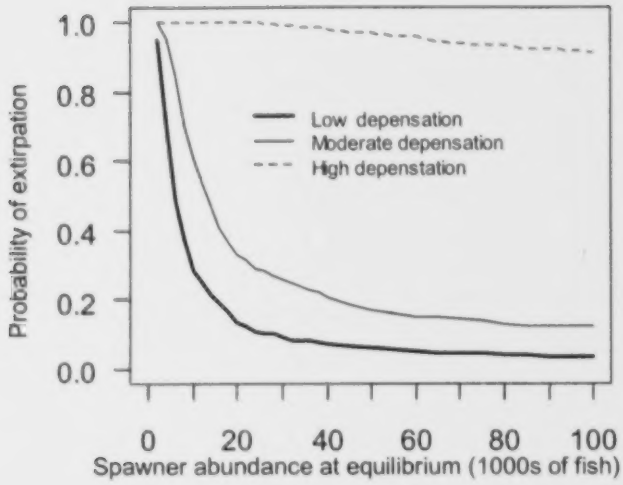


Figure 15. Probabilities of extirpation over the long term (100 years) for simulated populations of Pacific salmon under a constant fishing mortality rate policy equal to the lower benchmarks, F_{MSY}, and three assumptions about the spawner abundance below which depensatory mortality occurs: 500 fish (thick solid line); 1000 fish (thin solid line); 7000 (dashed line), over a gradient in equilibrium stock sizes (X-axis).

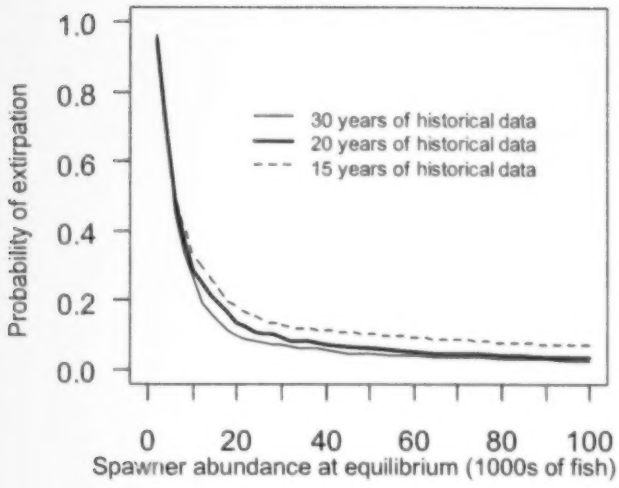


Figure 16. Probabilities of extirpation over the long term (100 years) for simulated populations of Pacific salmon under a constant fishing mortality rate policy equal to the lower benchmarks, F_{MSY}, and three assumptions about the number of years of historical data used to estimate F_{MSY} when deriving the lower benchmark (corresponding to the magnitude of assessment uncertainty): 30 years (thin solid line), 20 years (thick solid line), and 15 years (dashed line), over a gradient in equilibrium stock sizes (X-axis).

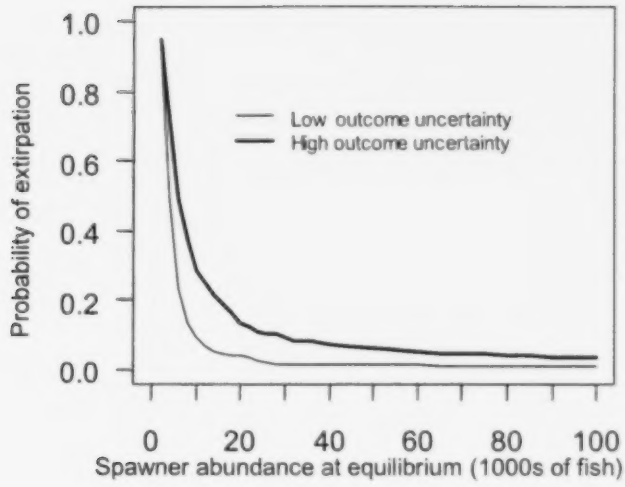


Figure 17. Probabilities of extirpation over the long term (100 years) for simulated populations of Pacific salmon under a constant fishing mortality rate policy equal to the lower benchmarks, F_{MSY}, and two assumptions about the magnitude of outcome uncertainty: standard deviation between realized harvest rates and targets = 0.097 (thin solid line) and 0.19 (thick solid line), over a gradient in equilibrium stock sizes (X-axis).

3.2 Model 2: Probability of recovery to S_{MSY} in one (or three) generations

3.2.1 Lower benchmarks on spawner abundances

Populations with initial spawner abundances equivalent to the lower benchmarks derived from S at 50-90% of R_{MSY} (black circles labeled 50-90% of R_{MSY}, Figure 18a), S at 50% of R_{MAX} (red circle), and 40% of S_{MSY} (blue circle) had high probabilities of recovery to S_{MSY} within one generation in the absence of commercial and recreational fishing (>75% probability, definition adapted from DFO's "Fishery decision-making framework incorporating the Precautionary Approach" (2009)) (Figure 18a). Populations that were initialized at S_{gen} (green circle, Figure 18a) and S at 30-40% of R_{MSY} (black circles labeled 30-40% of R_{MSY}, Figure 18a) had moderately high probabilities of recovery within one generation (50-75%). Probability of recovery within three generations were high or very high (>75% or >95% probability, respectively) for all benchmarks (Figure 18b).

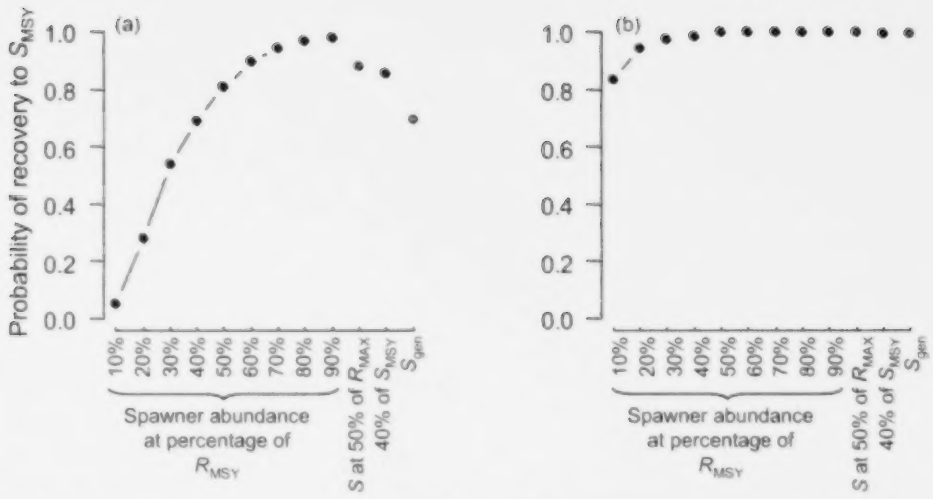


Figure 18. Probabilities of recovery over one (a) and three (b) generation(s) for simulated populations of Pacific salmon from lower benchmark on spawner abundances listed on the X-axis, in the absence of commercial and recreational fishing. Lower benchmarks derived from spawner abundances at various percentages of R_{MSY} (black solid circles) are compared with three other lower benchmarks: spawner abundances at 50% of R_{MAX} (red circle), 40% of S_{MSY} (blue circle), and spawner abundance resulting in recovery to S_{MSY} in one generation without fishing under equilibrium conditions, S_{gen} (green circle).

When we assumed populations were highly productive (mean Ricker "a" value = 2.0, equivalent to 7.4 recruits/spawner at low spawner abundances), probabilities of recovery within one generation were high (>75% probability) for all benchmarks except for S at 10-20% of R_{MSY} (Figure 19). In contrast, when we assumed populations were relatively unproductive (mean "a" value = 0.5, equivalent to 1.6 recruits/spawner at low spawner abundances), probabilities of recovery were moderately high (50-75%) for S at 50-90% of R_{MSY}, S at 50% of R_{MAX} and S_{gen}, and low for the remaining benchmarks. Similar to the results for probability of extirpation over the long term, those differences were relatively minor for the benchmark based on S_{gen} (green circles; i.e., performance of S_{gen} was relatively insensitive to variability in productivity levels), and relatively large for benchmarks based on R_{MSY} (black circles) and S_{MSY} (blue circles).

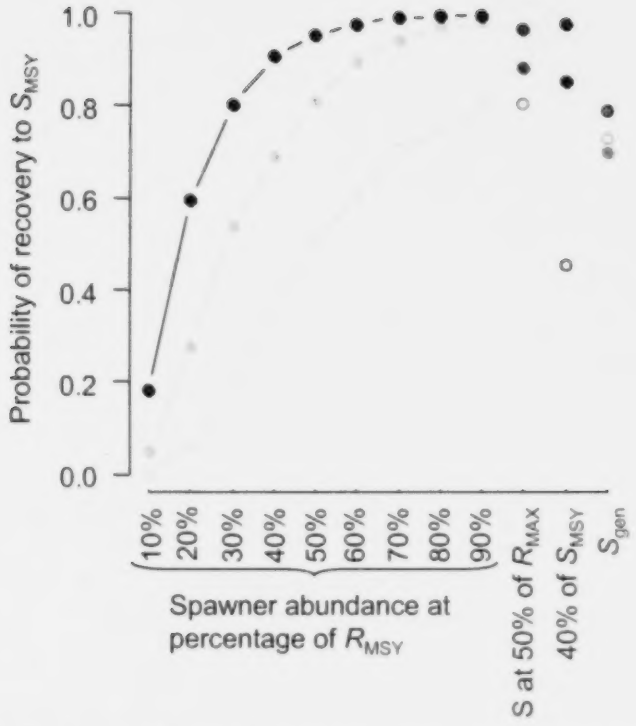


Figure 19. Probabilities of recovery over one generation for unproductive (hollow grey and coloured circles), moderately productive (solid grey and coloured circles), and highly productive (solid black and coloured circles with black outline) simulated populations of Pacific salmon from lower benchmarks on spawner abundances listed on the X-axis in the absence of commercial and recreational fishing. Lower benchmarks are the same as described in the caption to Fig. 18.

Probabilities of recovery to S_{MSY} were relatively insensitive to variability in assumptions about temporal trends in productivity (Figure 20), the form of the stock-recruitment relationship (Figure 21), the threshold below which depensation occurs (Figure 22), number of years used to estimate benchmarks (Figure 23), magnitude of outcome uncertainties (Figure 24), and the lower limit on harvest rates (Figure 25). In general, increasing uncertainty and harvest resulted in reduced probability of recovery to S_{MSY}.

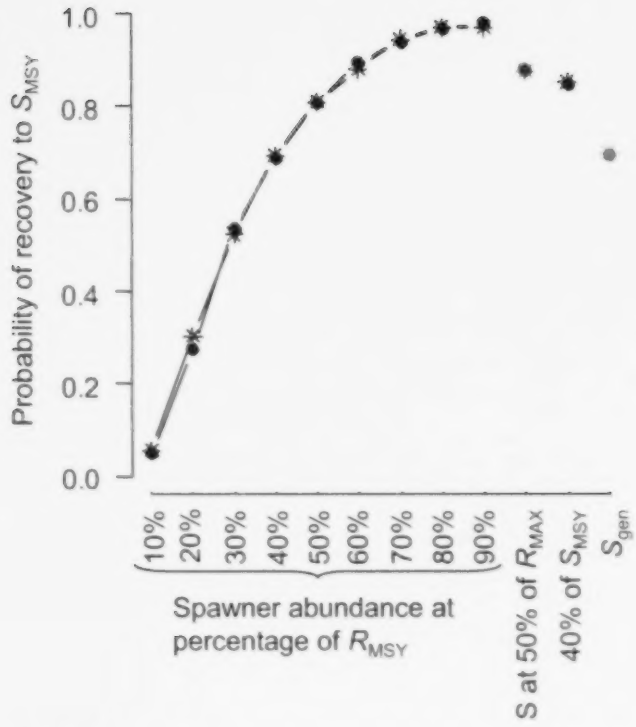


Figure 20. Probabilities of recovery over one generation for simulated populations of Pacific salmon that have constant productivity (Ricker "*a*" parameter) over time (hollow grey and coloured circles), linearly increasing productivity (solid grey and coloured circles), linearly declining productivity (solid black and coloured circles with black outline), and cyclic patterns in productivity (black and coloured asterisks), from lower benchmarks on spawner abundances listed on the X-axis in the absence of commercial and recreational fishing. Note, points are almost coincident because magnitudes of the changes in productivity are small over one generation. Lower benchmarks are the same as described in the caption to Fig. 18.

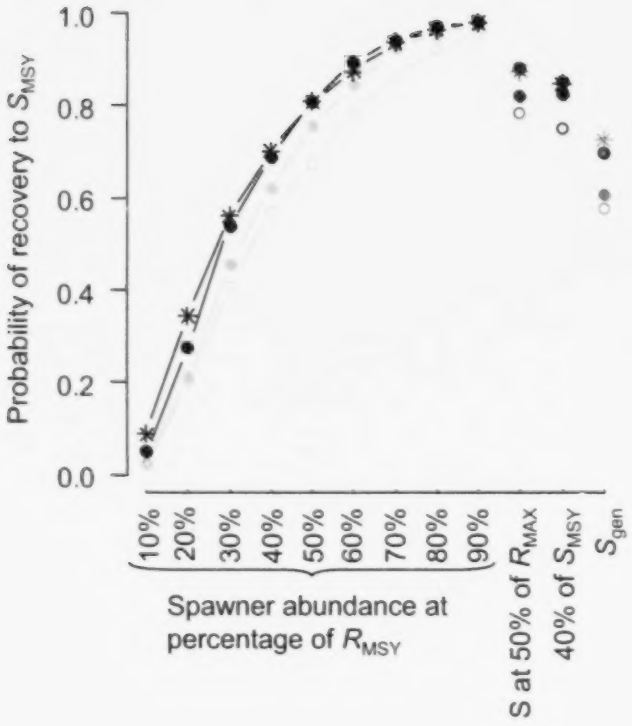


Figure 21. Probabilities of recovery over one generation for simulated populations of Pacific salmon that recruit according to a Ricker model (solid grey and coloured circles), a Ricker model with autocorrelation and depensation (solid black and coloured circles with black outline), a Beverton-Holt model (hollow grey and coloured circles), and a Larkin model (black and coloured asterisks), from lower benchmarks on spawner abundances listed on the X-axis in the absence of commercial and recreational fishing. Lower benchmarks are the same as described in the caption to Fig. 18.

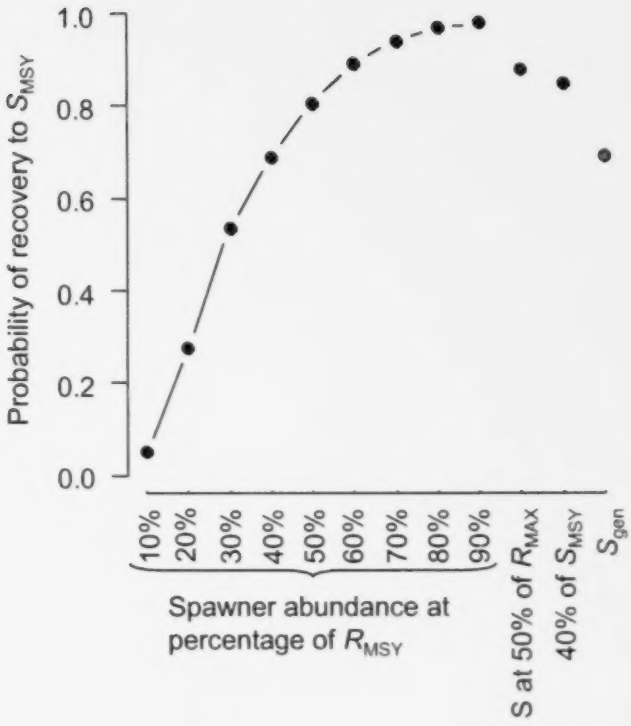


Figure 22. Probabilities of recovery over one generation for simulated populations of Pacific salmon that recruit according to a Ricker model with autocorrelation and depensatory mortality at low spawner abundances, i.e., below 500 spawners, 1000 spawners, and 7000 spawners, from lower benchmarks on spawner abundances listed on the X-axis, in the absence of commercial and recreational fishing. Note, points for different threshold levels below which depensation occurs are exactly coincident (i.e., the probability of recovery is insensitive to threshold level). Lower benchmarks are the same as described in the caption to Fig. 18.

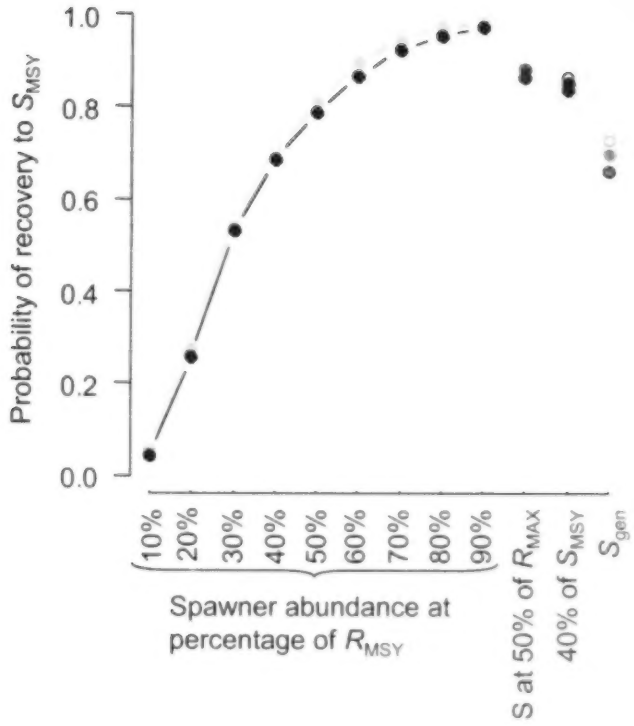


Figure 23. Probabilities of recovery over one generation for simulated populations of Pacific salmon from lower benchmarks on spawner abundances listed on the X-axis, derived from historical time series of length 15 years (solid black and coloured circles with black outline), 20 years (solid grey and coloured circles), and 30 years (hollow grey and coloured circles), in the absence of commercial and recreational fishing. Lower benchmarks are the same as described in the caption to Fig. 18.

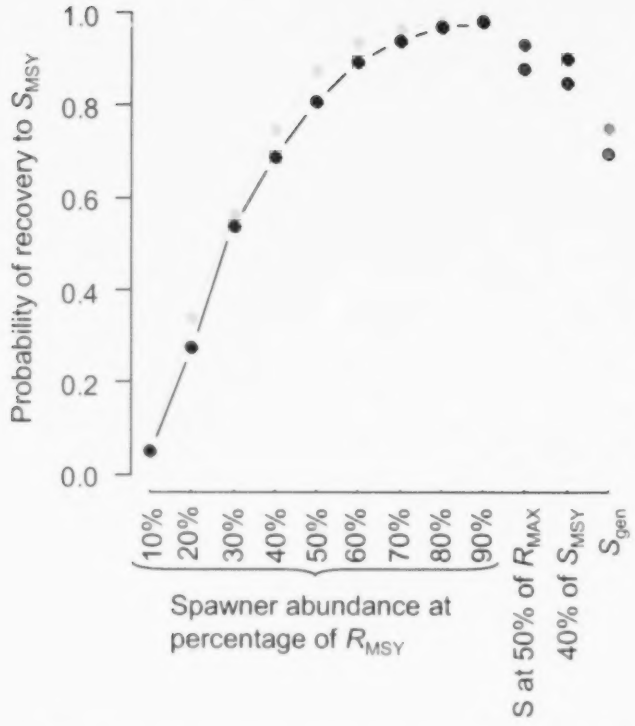


Figure 24. Probabilities of recovery over one generation for simulated populations of Pacific salmon with low outcome uncertainties (solid grey and coloured circles) and high outcome uncertainties (solid black and coloured circles with black outline), from lower benchmarks on spawner abundances listed on the X-axis, in the absence of commercial and recreational fishing. Lower benchmarks are the same as described in the caption to Fig. 18.

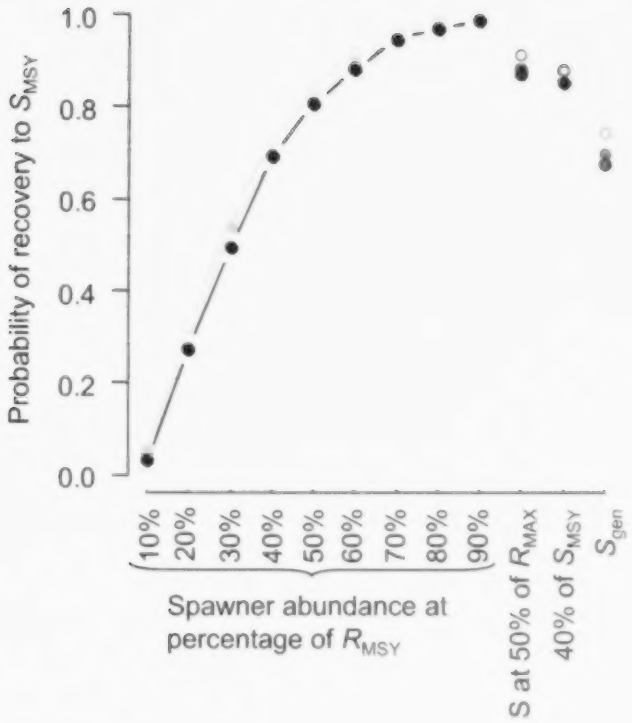


Figure 25. Probabilities of recovery over one generation for simulated populations of Pacific salmon from lower benchmarks on spawner abundances listed on the X-axis, in the absence of commercial and recreational fishing but with non-targeted harvest rate (e.g., from a test fishery and by-catch) of $h_t = 0.02$ (hollow grey and coloured circles), $h_t = 0.1$ (solid grey and coloured circles) and $h_t = 0.2$ ((solid black and coloured circles with black outline). Lower benchmarks are the same as described in the caption to Fig. 18.

3.2.2 Lower benchmarks on fishing mortality

When populations were subjected to fishing mortalities equal to the lower benchmarks, 70-150% of F_{MSY}, F_{MAX}, and F_{MED}, the probabilities of recovery to S_{MSY} within one generation were moderately low or low (probabilities <50% (Figure 26a). Only lower benchmarks, 40-50% of F_{MSY} had probabilities of recovery to S_{MSY} > 50% within one generation. However, when the time frame of recovery was extended from one to three generations, probabilities of recovery were high (>75% probability) for the benchmarks, 50-100% F_{MSY}, and moderately high (50-75% probability) for benchmarks, 110-140% F_{MSY}

and F_{MED} (Figure 26b). When we assumed that the population was highly productive, (mean Ricker "a" = 2.0), probabilities of recovery within one generation increased to > 50% for benchmarks, 50-90% F_{MSY}, but remained low for the other benchmarks (Figure 27). When we assumed the population was unproductive (mean Ricker "a" = 0.5), the probabilities of recovery within one generation were low for all benchmarks (probabilities <25%) (Figure 27).

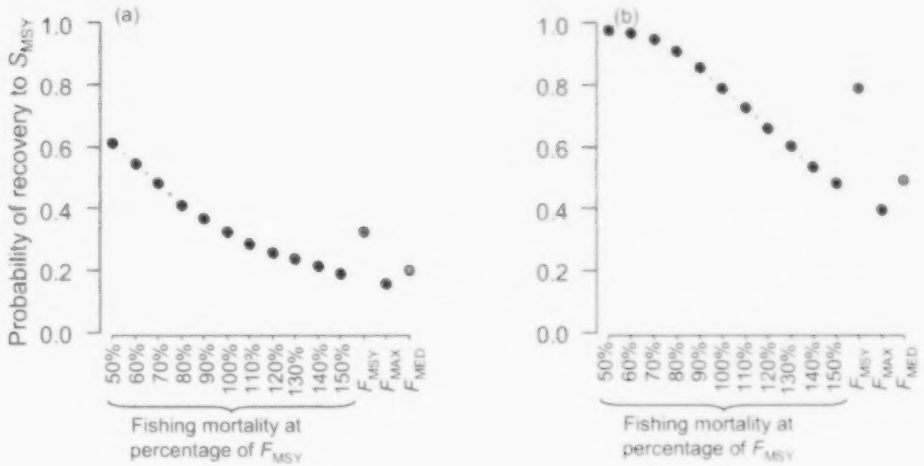


Figure 26. Probabilities of recovery over one (a) and three (b) generation(s) for simulated populations of Pacific salmon managed according to the lower benchmark on fishing mortality listed on the X-axis, in the absence of commercial and recreational fishing. Lower benchmarks derived from fishing mortality at various percentages of F_{MSY} (black solid circles) are compared with three other lower benchmarks: F_{MSY} (red circle), maximum $\log_e(R/S)$ at low spawner abundances, F_{MAX} (blue circle), and median $\log_e(R/S)$, F_{MED} (green circle).

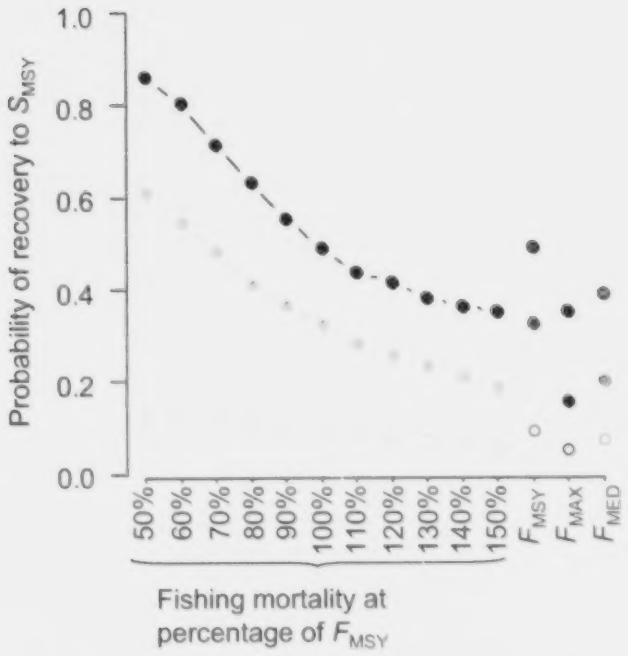


Figure 27. Probabilities of recovery over one generation for unproductive (hollow grey and coloured circles), moderately productive (solid grey and coloured circles), and highly productive (solid black and coloured circles with black outline) simulated populations of Pacific salmon managed according to the lower benchmarks on fishing mortality listed on the X-axis, in the absence of commercial and recreational fishing. Lower benchmarks are the same as described in the caption to Fig. 26.

Similar to the results for benchmarks on spawner abundances, probabilities of recovery for benchmarks on fishing mortality were relatively insensitive to time trends in productivity (Figure 28), the form of the stock-recruitment model (Figure 29), threshold level in spawner abundances below which depensation occurs (Figure 30), number of years of historical data used to estimate benchmarks (Figure 31), and the magnitude of outcome uncertainties (Figure 32). In general, increasing uncertainty and harvest resulted in reduced probability of recovery. For one exception, increasing outcome uncertainty resulted in a higher probability of recovery because occasional low harvest rates (below targets) improved performance (increased probability of recovery) more than high harvest rates reduced performance.

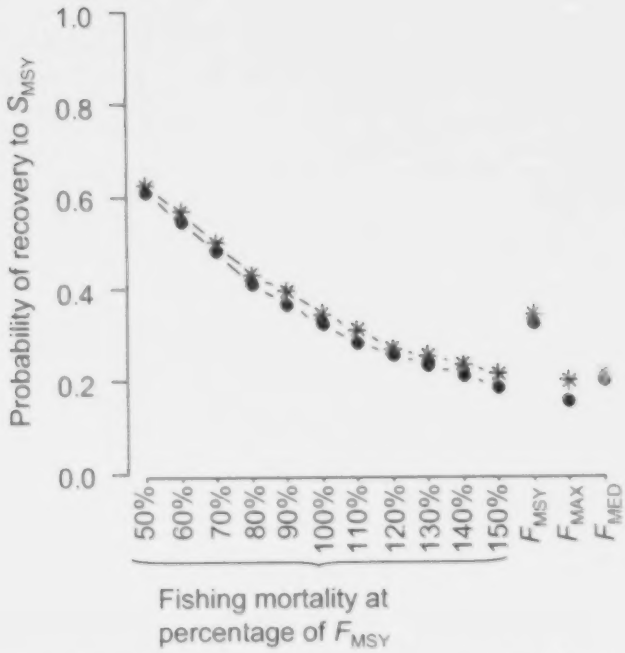


Figure 28. Probabilities of recovery over one generation for simulated populations of Pacific salmon that have constant productivity (Ricker "*a*" parameter) over time (hollow grey and coloured circles), linearly increasing productivity (solid grey and coloured circles), linearly declining productivity (solid black and coloured circles with black outline), and cyclic patterns in productivity (black and coloured asterisks), managed according to the lower benchmarks on fishing mortality listed on the X-axis in the absence of commercial and recreational fishing. Note, points are almost coincident because magnitude of the changes in productivity are small over one generation. Lower benchmarks are the same as described in the caption to Fig. 26.

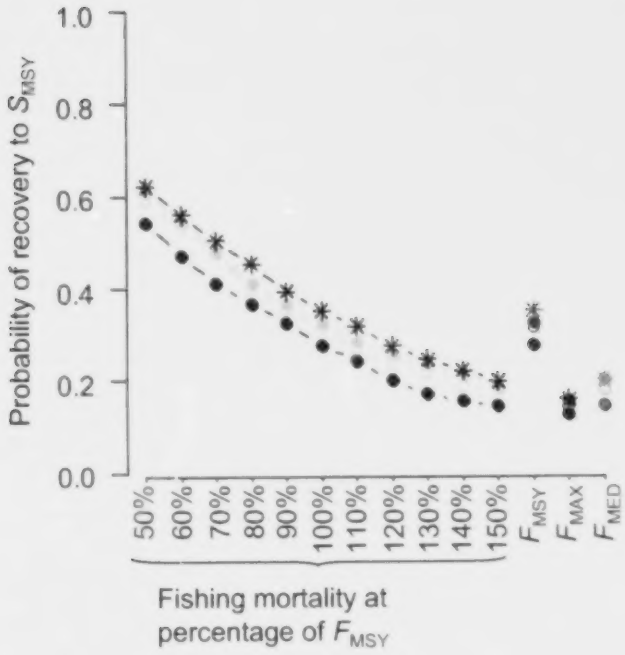


Figure 29. Probabilities of recovery over one generation for simulated populations of Pacific salmon that recruit according to a Ricker model (hollow grey and coloured circles), a Ricker model with autocorrelation and depensation (solid grey and coloured circles), a Beverton-Holt model (solid black and coloured circles with black outline), and a Larkin model (black and coloured asterisks), managed according to the lower benchmarks on fishing mortality listed on the X-axis in the absence of commercial and recreational fishing. Lower benchmarks are the same as described in the caption to Fig. 26.

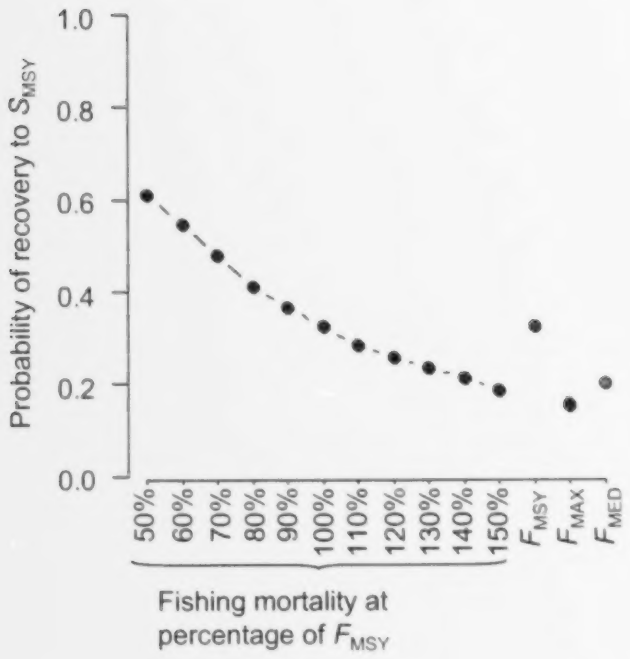


Figure 30. Probabilities of recovery over one generation for simulated populations of Pacific salmon that recruit according to a Ricker model with autocorrelation and depensatory mortality at low spawner abundances, i.e., below 500 spawners, 1000 spawners, and 7000 spawners, managed according to the lower benchmarks on fishing mortality listed on the X-axis, in the absence of commercial and recreational fishing. Note, points for different threshold levels below which depensation occurs are exactly coincident (i.e., the probability of recovery is insensitive to threshold level). Lower benchmarks are the same as described in the caption to Fig. 26.

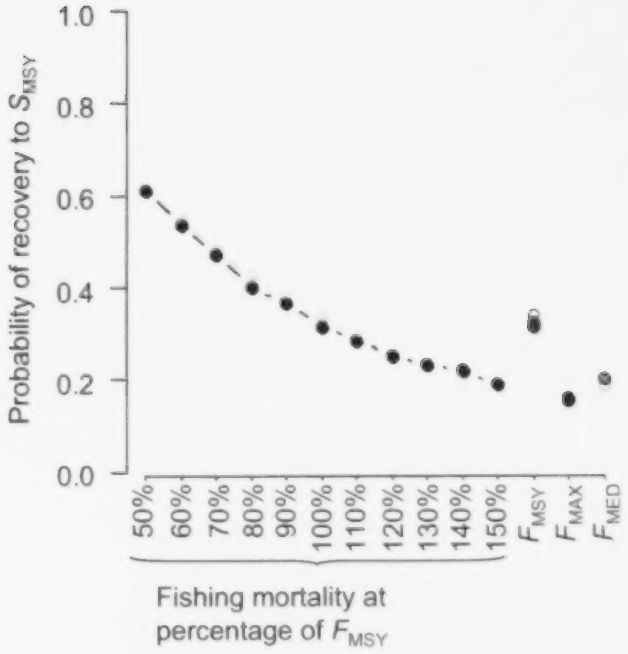


Figure 31. Probabilities of recovery over one generation for simulated populations of Pacific salmon managed according to the lower benchmarks on fishing mortality listed on the X-axis, derived from historical time series of length 15 years (solid black and coloured circles with black outline), 20 years (solid grey and coloured circles), and 30 years (hollow grey and coloured circles), in the absence of commercial and recreational fishing. Lower benchmarks are the same as described in the caption to Fig. 26.

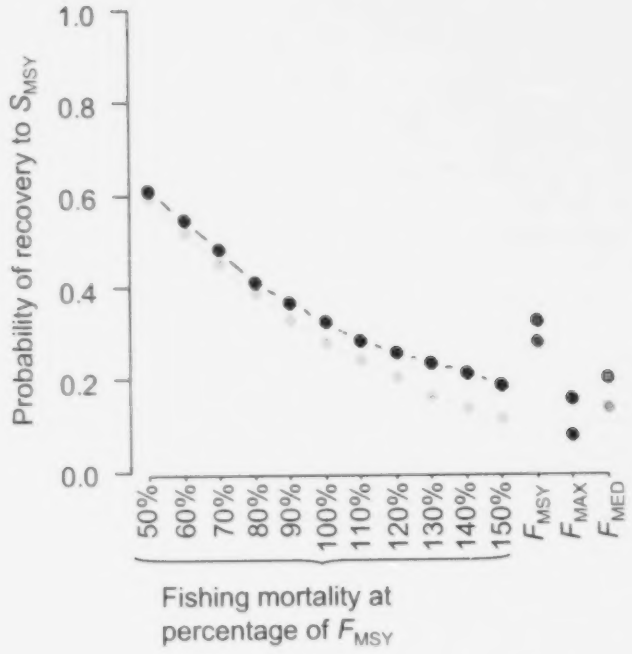


Figure 32. Probabilities of recovery over one generation for simulated populations of Pacific salmon with low outcome uncertainties (solid grey and coloured circles) and high outcome uncertainties (solid black and coloured circles with black outline), managed according to the lower benchmarks on fishing mortality listed on the X-axis, in the absence of commercial and recreational fishing. Lower benchmarks are the same as described in the caption to Fig. 26.

4. RECOMMENDATIONS

Although results from simulation models such as the one described here are typically highly sensitive to assumptions about model structure and parameterization (Dulvy et al., 2004), the relative performance of candidate management decisions (or lower benchmarks for status assessment) and their sensitivities to alternative model assumptions can provide useful information when evaluating management options (Mace et al., 2008). For metrics of spawner abundances, we suggest deriving a lower benchmark from S_{gen}, the abundance of spawner that will result in rebuilding to S_{MSY} under equilibrium conditions in the absence of fishing, because in our simulation model, the performance of S_{gen} (i.e., the probabilities of extirpation and recovery to a target) was more robust to variability in stock productivity than benchmarks calculated from proportions of S_{MSY}, S_{MAX}, or S at proportions of R_{MSY}. S_{gen} was also associated with a relatively low probability of extirpation over 100 years (probability <25%) for populations with equilibrium spawner abundances >15 000 fish, and high probability of recovery within three generations (probability >75%). S_{gen} was chosen by the BC Ministry of the Environment as a limit reference point (a level of abundance "that defines a highly undesired state" (Johnston et al., 2002, p.4)) for steelhead, *Oncorhynchus mykiss*, based on the results of a similar simulation modelling exercise. They further suggested that in the absence of data on stock productivity to calculate S_{gen}, 15% of carrying capacity (or between 10% and 20%) be used as a proxy lower reference point.

For metrics of fishing mortality, we suggest deriving a lower benchmark from F_{MSY} (fishing mortality at maximum sustained yield) because the probability of recovery for that benchmark was more robust to variability in stock productivity than benchmarks calculated from proportions of F_{MSY}, F_{MAX}, or F_{MED}. In addition, F_{MSY} was associated with a relatively low probability of extirpation over 100 years (probability <25%) when equilibrium abundances were > 30,000 fish, and high probability of recovery within three generations (probability >75%). Furthermore, that choice is consistent with the recommendation of F_{MSY} as a "limit reference point" by the UN Straddling Fish Stocks and Highly Migratory Fish Stocks Agreement (1995).

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